



**SYNTHESIS OF 3-DIMENSIONAL LIGHTNING DATA AND WEATHER  
RADAR DATA TO DETERMINE THE DISTANCE THAT NATURALLY  
OCCURRING LIGHTNING TRAVELS FROM THUNDERSTORMS**

THESIS

Lee A. Nelson, First Lieutenant, USAF

AFIT/GM/ENP/02M-07

DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY

***AIR FORCE INSTITUTE OF TECHNOLOGY***

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<b>Abstract</b> The goal of this research was to examine the possibility of establishing guidance for lightning avoidance and lightning warning criteria based upon lightning radar reflectivity signatures. Determining how far naturally occurring lightning normally travels from thunderstorms can provide insight to decision makers concerning in-flight and ground safety measures. 3D lightning data are merged with archived weather radar data. To analyze the radar characteristics of the lightning data, radar data are interpolated to a 3D grid of reflectivity. Lightning flashes were analyzed to resolve the reflectivity of the flash origin and to determine the distance of the flash origin from the nearest radar reflectivity core--defined as a radar reflectivity factor (dBZ) of greater than 40-dBZ. 95% of the flash origins were located within 3 km of the nearest 40-dBZ composite reflectivity echo, while 95% of the flash origins were within 6 km of the nearest 40-dBZ base reflectivity echo. 99% of the flashes traveled less than 30 km from the flash origin, and less than 21 km from the nearest 40-dBZ echo. The results indicate that it should be feasible to suggest lightning avoidance criteria based upon the radar reflectivity from ground or airborne radars.		

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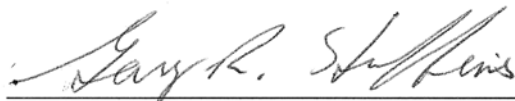
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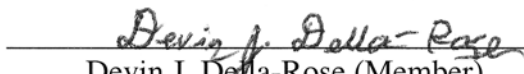
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Lee A. Nelson

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## **Abstract**

Lightning has an impact on Air Force operations in the air and on the ground. Delays to flight or maintenance activities are some of the common consequences that result from thunderstorms approaching an active airfield. These delays can degrade a unit's mission effectiveness, but their impact is nothing compared to the potential fallout when valuable equipment, or much worse when personnel, are struck by lightning. As such, determining how far naturally occurring lightning normally travels from thunderstorms can provide insight to decision makers concerning in-flight and ground safety measures.

3D lightning data from the Kennedy Space Center was merged with archived weather radar data from Melbourne, Florida. To analyze the radar characteristics of lightning, the radar data was interpolated to a 3D grid of reflectivity to permit direct extraction of reflectivity values. More than 19,000 lightning flashes were analyzed to resolve the composite reflectivity of the flash origin and to determine the horizontal distance of the flash origin from the nearest radar reflectivity core—defined as a radar reflectivity factor (dBZ) of greater than 40 dBZ. More than 8,500 flashes were used for similar base reflectivity computations.

95% of the flash origins either had a composite reflectivity of greater than 40 dBZ or were within 3 km of the nearest 40-dBZ radar echo. 95% of the flash origins had a base reflectivity of greater than 40 dBZ or were within 6 km of the nearest 40-dBZ echo. In addition, 99% of the flashes traveled less than 30 km from the flash origin, and less than 21 km from the nearest 40-dBZ echo. Based upon these results, it should be feasible to suggest lightning avoidance criteria based upon the radar reflectivity displayed by ground or airborne radars.

# **SYNTHESIS OF 3-DIMENSIONAL LIGHTNING DATA AND WEATHER RADAR DATA TO DETERMINE THE DISTANCE THAT NATURALLY OCCURRING LIGHTNING TRAVELS FROM THUNDERSTORMS**

## **I. Introduction**

### **1.1. Motivation**

Lightning is a common natural phenomenon that can adversely affect Air Force ground and aerospace operations. The impact that lightning has on mission effectiveness can range from mild to the extreme. A lightning-producing thunderstorm approaching a base, prompting the Base Weather Station (BWS) to issue a weather warning, will cause all maintenance activities on the flight line to be halted immediately as personnel take shelter (Department of the Air Force 1997). A delay in the maintenance schedule may be a mere annoyance; it could, however, have a very significant impact on overall mission capability. Even a severe delay in maintenance and flight operations that degrades a unit's effectiveness is insignificant when compared to the potential lethality—to both personnel and valuable equipment—of actually being struck by lightning.

An aircraft struck by lightning may incur anything from minimal damage to the skin of the aircraft to catastrophic system failure. Given the nature of modern military aircraft design, especially those airframes with stealth characteristics where the skin is made up of composite materials, even seemingly modest damage to the aircraft's outer surface can be extremely expensive to repair. Aircraft parked on the flight line and the

personnel that maintain them, are in jeopardy of being struck by cloud-to-ground lightning. Once airborne, however, the threat of lightning strikes also includes the much more prevalent cloud discharges that never reach the ground. The desire for rather liberal lightning avoidance flight restrictions to allow for more flight hours—especially in the summer months when afternoon thunderstorms are present across much of the southern United States—must be weighed against the concerns for the safety of the crewmembers, passengers, and valuable cargo.

A key element in coming up with recommendations for aircraft in-flight lightning avoidance is determining the distance that naturally occurring lightning travels from thunderstorm radar echoes. Most modern military aircraft have onboard radars that are capable of interrogating thunderstorms. A study of the radar characteristics of lightning source regions, when coupled with information about the extent that naturally occurring travels, could, potentially, provide the basis for improved guidance on lightning avoidance. The same holds true for verification criterion for issuing and canceling lightning warnings at Air Force installations; the distance that cloud-to-ground lightning normally travels from its source to the ground strike location is of particular interest in examining this radius. If the distance that cloud-to-ground lightning travels can then be correlated with a radar echo signature of the source, better guidance for BWS personnel may be possible.

## **1.2. Problem and Importance**

Personnel struck by lightning can be severely injured, or even killed; no asset in the Air Force inventory is more precious than the people that make up the force. In a tragic event that took place at Hurlburt Field, Florida on 29 April 1996, a young airman

lost his life after being struck by lightning while maintaining an AC-130H aircraft (Bauman 1998). At 0804 CDT the BWS issued an advisory for observed lightning within 3 NM. The advisory remained in effect for the next hour and twenty minutes with no further lightning observed within 3 NM of the airfield during that time. At 0930 CDT the advisory was cancelled, with an indication that it may need to be reissued within the next 30 minutes. Immediately after the advisory was cancelled, a maintenance crew was dispatched to resume a training class on AC-130H tire replacement procedures. At 0938 CDT, while one of the airman was in the wheel well of the AC-130H, a bolt of lightning struck the aircraft. Ten personnel were injured, and the airman that was in the wheel well was killed. Air traffic controllers estimated that the thunderstorm that caused the lightning was about 5 – 7 NM south of the airfield.

As a result of the events of 29 April 1996, weather warnings for lightning at all Air Force installations are to be issued when lightning is observed within 5 NM (Department of the Air Force 1998). According to this Air Force Manual (AFM), the warning is to stay in effect until the, “thunderstorms have passed beyond the area covered by the warning.” Perhaps nothing could have prevented the tragedy that occurred that day; the investigation found that all parties involved—the BWS, maintenance, and medical personnel—had done everything right based upon the information available to them (Bauman 1998). But, is it possible that even the 5-NM criterion—which is declared in AFM 15-125 (1998) to be the minimum distance to be used to trigger a lightning warning to be issued or cancelled—is not adequate? Also, when trying to determine when the thunderstorm has moved out of the area to warrant canceling a warning, what should the BWS personnel use to determine how far away the thunderstorm is? Can a

rule-of-thumb that uses radar information be ascertained that will take some of the uncertainty out of this process? But, cloud-to-ground lightning is not the only concern.

The System Program Office (SPO) for the C-17 Globemaster III requested information about how far lightning travels from thunderstorms so better guidance on lightning avoidance could be given to aircrews. It is estimated that an Air Force C-17 is struck by lightning approximately once every 4,400 hours of operation (C-17 TIM Brief 2001). Information about lightning avoidance is, however, of general interest to the entire U.S. Air Force flying community. Answering the questions posed in the previous paragraph is the goal of this work along with two other studies being accomplished this year at AFIT—the other theses are by Captain Todd McNamara and Captain David Vollmer. When the results of this work and the other two projects are combined, it should provide better guidance to decision makers about both the cloud-to-ground lightning safety issue and in-flight lightning avoidance criteria for military aviation assets.

### **1.3. Purpose and Scope of Work**

The purpose of this research is to examine the radar reflectivity signatures of lightning flashes to determine if it is possible to establish guidance for aircraft lightning avoidance and improved criteria for issuing/canceling lightning warnings based upon these radar signatures. For this study, the thresholds of radar reflectivity factor displayed by the C-17's radar system are used to define a critical reflectivity value (40 dBZ) for identification of thunderstorm reflectivity cores. This allows an analysis of the radar reflectivity characteristics of lightning flash origins based upon ground-based weather radar observations to be applicable to what an aircrew member would see on their radar



display. The fusion of these lightning base reflectivity signatures with determinations of the distances lightning travels from the origin points, may aid in developing a rule-of-thumb for aircraft lightning avoidance. In addition, the lightning flash origin composite radar reflectivity signature, when coupled with Captain McNamara's results about distances of cloud-to-ground lightning, can provide valuable information about lightning warning criteria.

Three-dimensional lightning data from the Lightning Detection and Ranging (LDAR) system at the Kennedy Space Center (KSC), in conjunction with the weather radar coverage of the KSC area provided by the National Weather Service's (NWS) Weather Surveillance Radar – 1988 Doppler (WSR-88D) at Melbourne, Florida, makes an examination of lightning phenomenon in the KSC area a natural choice for this task. Raw LDAR data sets are archived and available for download from the Global Hydrology Resource Center, and WSR-88D data are available in archived format on 8mm data tape from the National Climatic Data Center (NCDC). The nature of working with archived radar data makes it unfeasible to conduct a broad survey that merges all available LDAR and radar data. As such, case studies are selected that provide data for two differing weather regimes that impact the KSC area. The geographic restriction imposed by the fact that the only 3D lightning data readily available are from the KSC, is a major limiting factor on the scope of this research.

Another limiting factor is that only naturally occurring lightning is being considered. In an article that appeared on the web-based magazine, Aerospace Engineering Online, Lalande et al. (1995) assert that about 90% of all aircraft lightning strikes are cases of triggered lightning, rather than naturally occurring lightning that is

intercepted by the aircraft. This triggered lightning occurs when an aircraft flies into a region of a thunderstorm where a very intense electrostatic field—in the range of 50 – 100 kV/m—is present. The fact that the intent of this study is to provide better guidance on thunderstorm avoidance mitigates the impact of this constraint.

#### **1.4. Summary of Results**

More than 19,000 lightning flashes were merged with weather radar data to determine the typical composite radar characteristics of lightning flash origin points. The radar reflectivity factor (dBZ) used to identify the reflectivity cores of thunderstorms is 40 dBZ. 95% of all the flash origins were either within a 40-dBZ echo, or were less than 3 km from the edge of the nearest 40-dBZ echo. For base reflectivity analysis, it was found that 95% of the more than 8,500 flash origins considered were less than 6 km from the nearest 40-dBZ reflectivity core. In order to provide guidance on lightning avoidance based upon radar echoes for weather or aircrew personnel, information about the extent of lightning from the flash origin points, and from the radar reflectivity cores, was also examined.

The maximum horizontal distance for each flash, measured from the flash origin point to each subsequent point in the lightning flash, of the 19,000+ lightning flashes in the composite reflectivity dataset was calculated. 99% of the flashes traveled less than 30 km from their origin, and 95% extended less than 19 km from the flash origin. In addition to these horizontal distance determinations, the maximum flash distance from a 40-dBZ echo, which represents the actual distance measured from each point in a flash to the nearest 40-dBZ echo in three dimensions, for the 8,515 flashes in the base reflectivity

dataset was also computed. 99% of these flashes traveled no more than 21 km from the nearest 40-dBZ echo.

Combining the flash origin radar characteristics with information about the overall extent of the lightning from the origin provides the data necessary to suggest potential lightning avoidance and lightning warning criteria based upon radar echoes. For example, it may be possible to suggest that weather warnings for lightning within five nautical miles of an Air Force installation could be issued when the 40-dBZ composite reflectivity echo of a lightning-producing thunderstorm comes within 7 NM of the advisory area. This could add to the overall safety of base personnel by not waiting to issue an advisory until lightning is actually observed within 5 NM.

The data also suggests that a possible lightning avoidance rule for aircraft would be to stay at least 36 km (or about 20 NM) away from the 40-dBZ radar reflectivity cores in thunderstorms. Also, much less restrictive avoidance criteria might be suggested by basing the rule on the finding that 99% of lightning flashes traveled no more than 21 km from the nearest reflectivity core. At the very least, this may show that the 20 NM avoidance rule would, indeed, be adequate.

## **1.5. Thesis Organization**

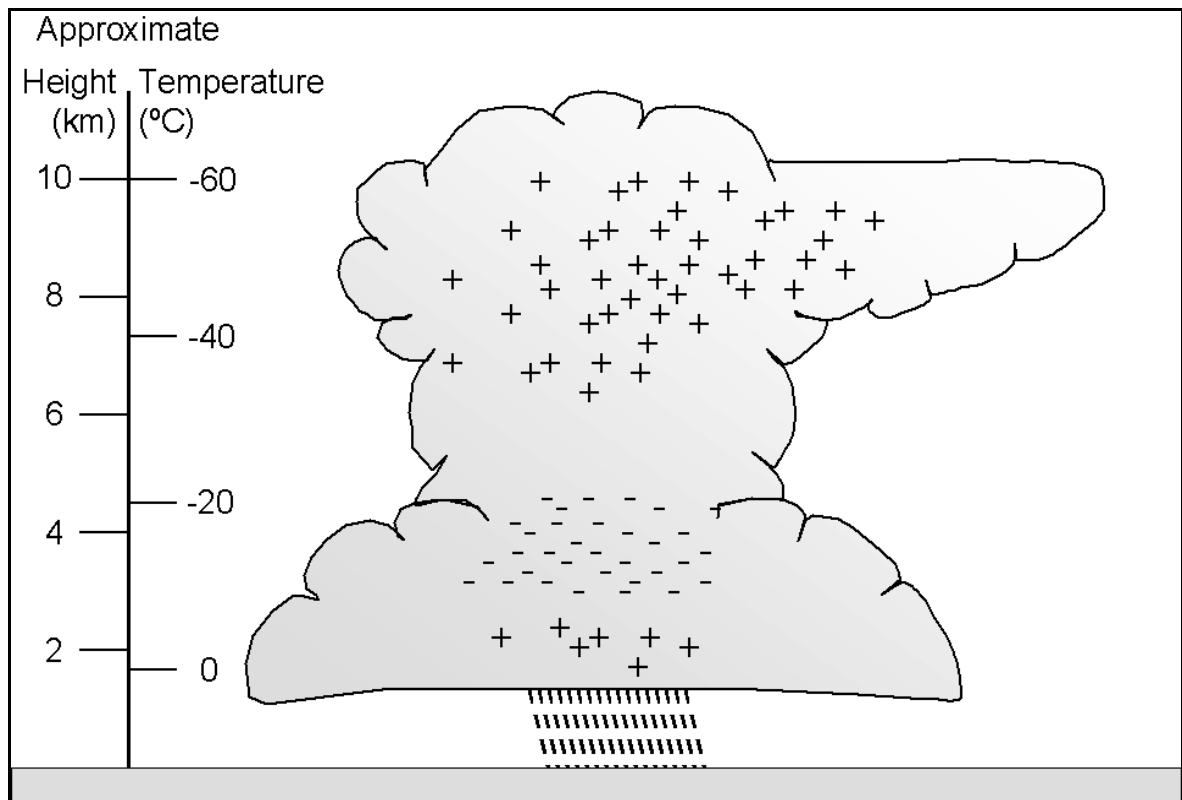
This initial chapter served as a brief introduction to the research topic and its importance to the Air Force. The next chapter is designed to allow the reader to gain insight into some necessary background information. A very brief discussion of lightning basics is presented, followed by information about the LDAR system at the KSC. The radar coverage over the KSC area is also detailed. Chapter three describes the methodologies employed to process the LDAR and radar data and to merge the resulting

data sets. A brief explanation of how case study days were chosen is presented as well. Analyses of the findings of this research are offered in the fourth chapter. The final chapter outlines the conclusions reached and suggests possible future research that could further this project.

## II. Background

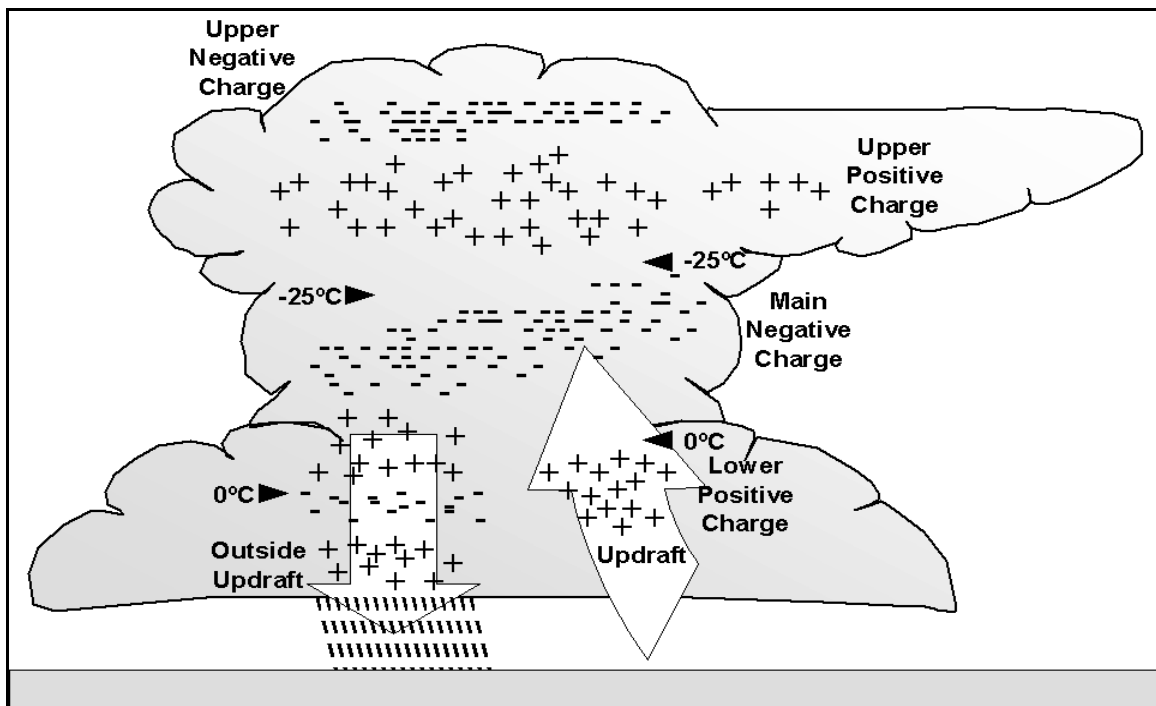
### 2.1. Thunderstorm Electrical Structure

The conceptual model of the electrical charge distributions in thunderstorms has evolved as better measurement techniques have been developed. The classical tripole model of thunderstorm charge distribution was developed in the 1920s and 1930s based upon ground-based electric field measurements (Uman and Krider 1989). Figure 1 depicts the classic tripole model, which consists of a main negatively charged region below the main (upper) positively charged region plus a lower positively charged region.



**Figure 1. Classic tripole model of charge distribution.** Tripole model consists of a main negative region below a main (upper) positively charged region, plus a weak, lower, positive region. (adapted from McIlveen 1992).

A more detailed conceptual model, based upon balloon soundings of the electrical structure of thunderstorms from three different types of convection: organized multicell, isolated super-cell, and multicell airmass, has recently been suggested (Stoltzenburg et al. 1988). The charge distributions in this new model are more complex than the classic tripole model, however, there are traits that are common to all three types of convection. Figure 2 shows this new paradigm with four charged regions in the vertical column around the updraft and six charged regions outside of the updraft. It is asserted that the classic tripole model may be imbedded in these charge regions. With this model in mind, we can now examine the lightning discharge.



**Figure 2. Modified conceptual model of charge distribution.** The modified model of charge distribution shows four charged regions in the updraft region of the storm and six charged regions outside the updraft region. (adapted from Stoltzenburg et al. 1998).

## **2.2. The Lightning Discharge Process**

Uman and Krider (1989) define lightning as, “a transient, high-current discharge with a path length measured in kilometers.” Lightning is classified in four basic ways: (1) lightning that occurs wholly within the cloud, (2) cloud-to-cloud discharges, (3) cloud-to-air discharges, and (4) cloud-to-ground lightning (CG). These first three types of discharges are collectively known as cloud discharges as they never actually reach the ground. It is estimated that for every CG discharge in the continental United States, there are almost three cloud discharges (Boccippio et al. 2000). However, much more is known about the processes that take place during CG lightning, so we’ll first examine CG basics to get a better understanding of what may be occurring in cloud discharges.

**2.2.1. CG Lightning.** Most of the research accomplished to date has focused primarily on CG lightning. Two of the primary reasons are that it poses a much greater threat to human life and property, and it is also easier to study using optical techniques (Uman and Krider 1989). Lightning discharges between cloud and Earth can be either positive or negative—as determined by the dominant charge present at the source region. CG discharges of either polarity can be initiated from the cloud downward, or much less frequently from the ground upward. Uman and Krider (1989) point out that negative downward-propagating CG flashes account for about 90% of all CG lightning worldwide.

A negative CG flash can lower tens of coulombs of negative electrical charge to Earth and last for about half a second (Uman and Krider 1989). A single lightning flash can have several high-current pulses called strokes. These strokes occur on order of only a millisecond with a slight delay of tens of milliseconds between strokes. In order for a

stroke to occur, a pathway must be present. The channel that transports the charge is called a stepped leader.

When the charged region in part of a cloud reaches a critical threshold, a preliminary breakdown occurs and a stepped leader is initiated (Uman and Krider 1989). These leader steps are typically about 1  $\mu$ s in duration, 50 m in length, and have a delay between steps of 20 to 50  $\mu$ s. As the stepped leader nears the ground, the electric field on the ground builds until the breakdown strength of the air is exceeded. When this happens, upward-moving discharges are initiated from sharp objects on the ground or irregularities on the surface (Uman and Krider 1989).

When one of these upward-moving discharges meets the downward-moving stepped leader, the leader is effectively connected to ground potential and an ionizing wave of ground potential propagates up the ionized leader channel (Uman and Krider 1989). This is the first return stroke, which typically lasts on order of 100  $\mu$ s. The leader channel is heated to a peak temperature of about 30,000 K due to the rapid release of energy (Uman and Krider 1989). As a result of the temperature increase, the channel expands and causes a compression wave that becomes thunder. If enough cloud charge is still available after the first return stroke, a dart leader can propagate down the original path and trigger further return strokes.

The peak current in a positive CG flash is typically much greater than that of a negative CG flash, but much less is known about the exact nature of positive CG flashes (Uman and Krider 1989). The stepped-leaders in a positive CG discharge are normally not as discretely stepped as they are in a negative flash. Positive flashes normally only



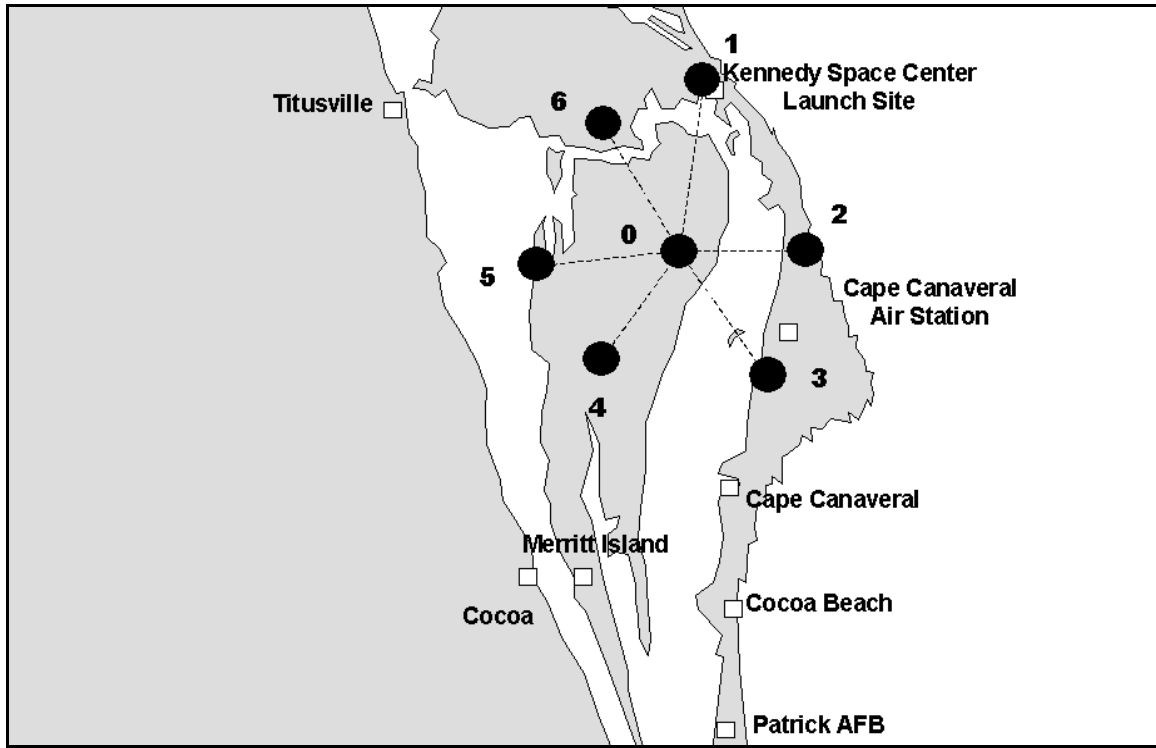
have one return stroke and positive flashes are much more common in winter than in summer months (Uman and Krider 1989).

**2.2.2. Cloud Discharges.** Until recently, there was no reliable way to understand the structure of cloud discharges, but the development of three-dimensional lightning mapping systems has opened the door to a better understanding of what is occurring within the cloud (Rison et al. 1999). Examination of data from these systems has confirmed that, normally, a bipolar breakdown occurs between the main negative and the upper positively charged regions of a cloud. Cloud discharges can move tens of coulombs of charge over a distance of 5 to 10 km, or more (Uman and Krider 1989). Both CG flashes and cloud discharges release electromagnetic energy as they propagate through the atmosphere; these 3D lightning detection systems take advantage of that fact to aid in locating where these events are taking place.

### **2.3. Lightning Detection and Ranging (LDAR)**

The LDAR system was developed primarily by Carl Lennon, a former National Aeronautical and Space Administration (NASA) engineer, in the mid-1970's in support of lightning research efforts at the KSC in Florida (Starr et al. 1998). The system consists of seven VHF antennas separated by 5-10 km located near the KSC launch facilities (Figure 3). Pulses of VHF energy emitted during the stepped leader process of a lightning event are located in east/west, north/south, and height coordinates from the central site. It locates these points by determining the relative difference in the time of arrival (TOA) of a VHF pulse at several antennas in the array. The central site antenna is the critical element of this system architecture; it must detect a signal for any processing

to occur (Starr et al. 1998). To understand how the system determines the location of an event, we will examine the data flow in the system.



**Figure 3. KSC LDAR Antenna Locations.** This map of the KSC area shows the relative locations of the seven antennas in the LDAR array. The antennas are separated by about 5 – 10 km and are spread out about the LDAR central site—site 0 on the map. (Adapted from Starr et al., 1998).

**2.3.1. Data Flow in LDAR System.** The RF energy that the system detects is in the VHF region centered at 63 MHz, which is in the middle of the spectrum allocated to television channel 3 (Lennon and Maier 1991). This frequency was chosen not only because it is within the spectrum of pulse energy emitted by lightning processes, but also because there was no local channel 3 operating in the KSC area when the system was designed. When the central site detects an RF pulse that exceeds a certain threshold, the

system is triggered and the remote antennas transmit time of arrival data to the central site (Lennon and Maier 1991).

The same pulse of RF energy detected by the central site may actually arrive at one, or more, of the remote antennas before being detected by the central site. The processing that takes place at the remote sensor sites, however, ensures that the central site will receive the direct signal before any of the timing data is received from the remote sites. When a detected event triggers the system, a 100  $\mu$ s data analysis period begins (Murphy et al. 2000). Once the data analysis period ends, the relative TOA of the pulse at the remote antennas is calculated and the time difference is used to determine the position of the event. This location process involves hyperbolic triangulation (Rustan et al. 1980). The data are then sent to a display workstation for graphical display and are also tagged with the appropriate position and timing data and cataloged digitally. With this basic understanding of how the LDAR system detects and locates VHF pulses emitted by the lightning process, it's important to gain some insight into just how accurate this location is.

**2.3.2. Accuracy of LDAR Data.** The accuracy of LDAR data is a function of the range from the central site and the altitude of the event (Murphy et al. 2000). Most of the altitude errors are linked to the fact that all LDAR elevation calculations are based upon a flat plane earth and do not account for curvature of the Earth—although these curvature errors are only significant outside of about 100 km range from the LDAR location (Boccippio et al. 2001). The range error is the paramount accuracy issue with LDAR data. Maier et al. (1995) found the median range error to be about 1km location error at a 40 km range from the LDAR central site; this was determined by using a signal

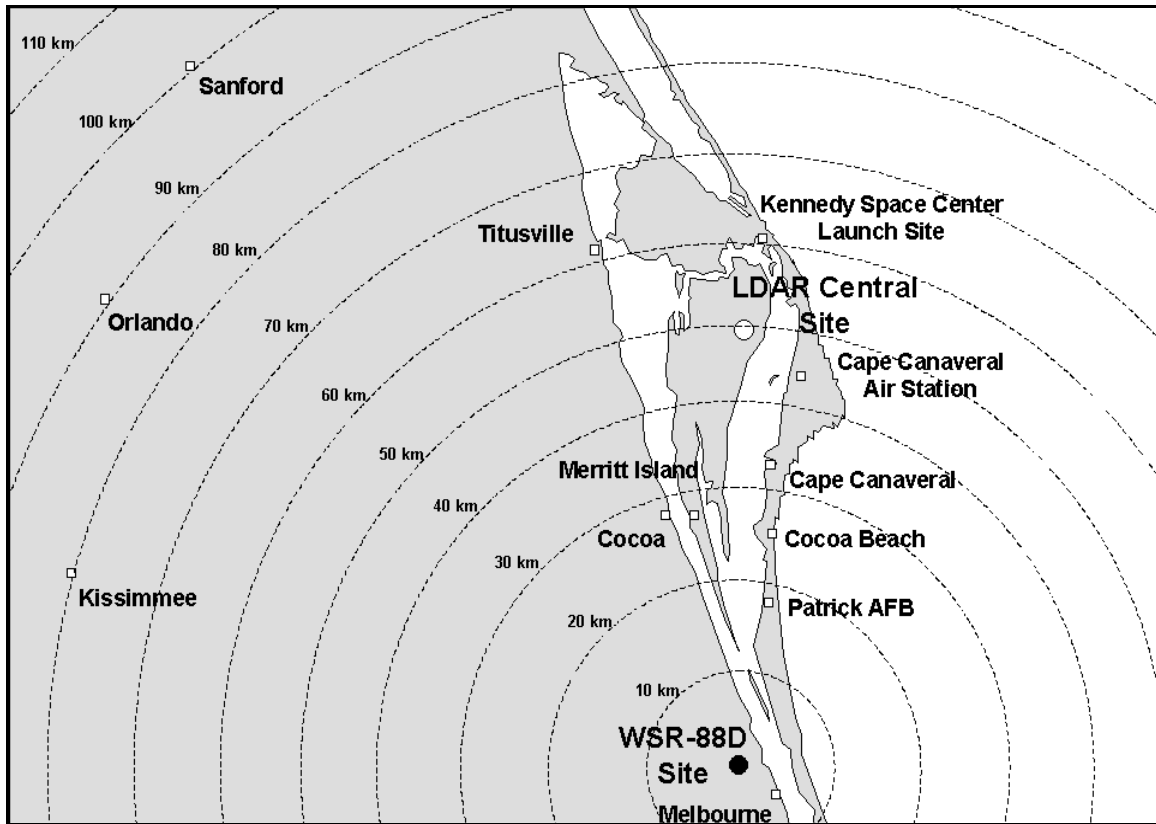
generator aboard an aircraft and comparing the known aircraft locations with LDAR derived locations. One of the primary causes of the range inaccuracy stems from a difficulty in precisely determining the TOA of the peak of a signal in a pulse of RF energy (Boccippio et al. 2001).

#### **2.4. Radar Coverage of the Kennedy Space Center Area**

The WSR-88D at the NWS field office in Melbourne, Florida provides good weather radar coverage of the KSC area. Their radar is located 1.13 km west and 47.32 km south of the LDAR central site. The height of the radar beam over the KSC area can be determined (with reasonable accuracy) using the following equation (Rinehart 1997):

$$H = \sqrt{r^2 + R'^2 + 2rR' \sin \phi} - R' + H_0 \quad (1)$$

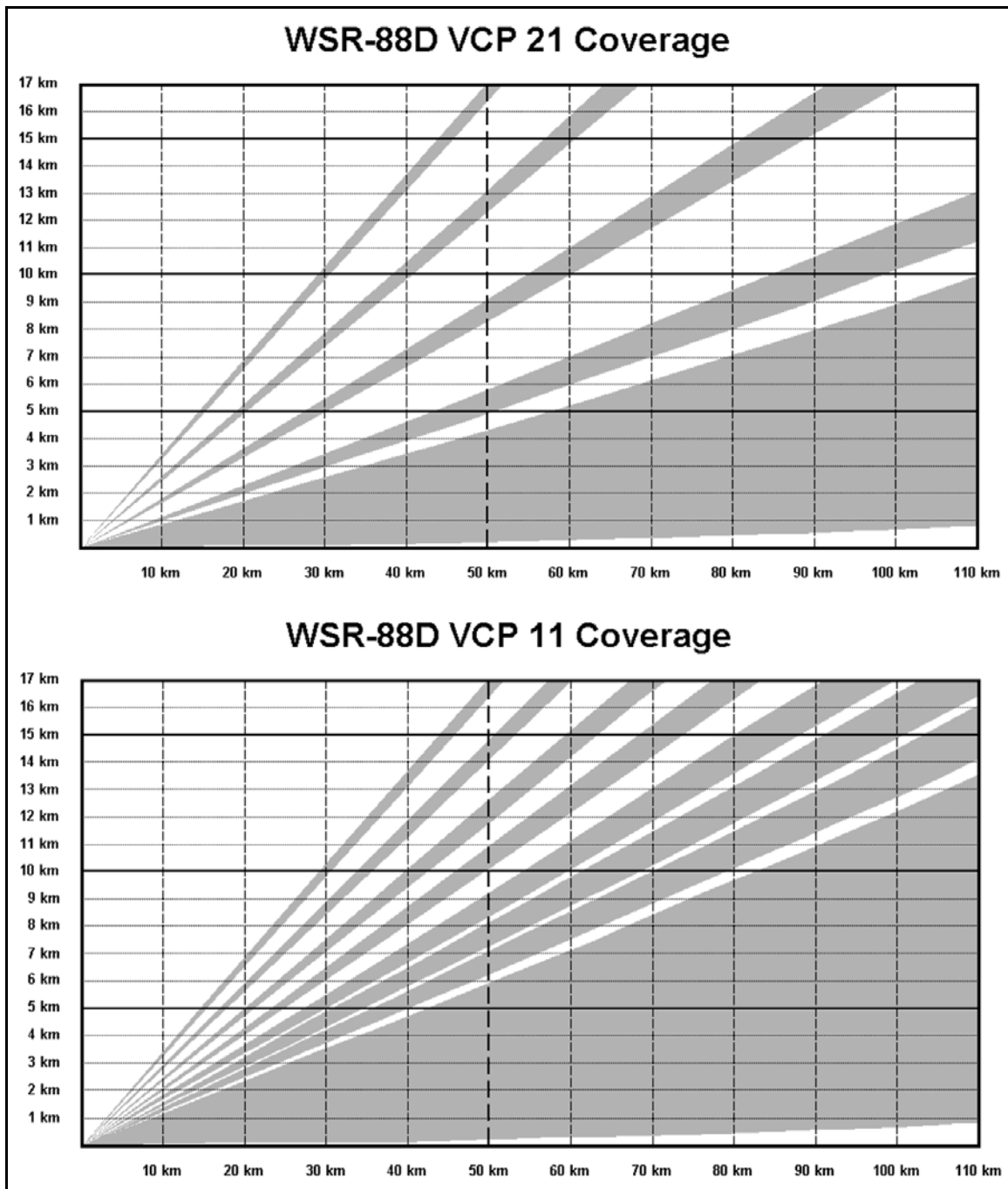
where  $H$  is the height of the center of the beam,  $r$  is the range to the point of interest from the radar,  $\phi$  is the elevation angle in degrees of the radar scan—0.5 degrees for the lowest WSR-88D elevation scan,  $H_0$  is the height of the radar antenna—about 30 m for the WSR-88D, and  $R'$  is the effective radius of the earth which accounts for the refractive index gradient along the path of propagation. All calculations and grid interpolations used in this project are based upon the assumption of standard refractivity using  $R' = (4/3)R$ , where  $R$  is the radius of the earth—assumed to be constant at 6374 km for the volume coverage pattern (VCP) and beam height calculations shown here. These assumptions lead to an estimated central beam height of just over 600 m above the center of the LDAR network for the lowest elevation angle. Figure 4 shows the relative position of the WSR-88D to the KSC area.



**Figure 4. Map of Melbourne WSR-88D location.** This map shows the relative position of the Melbourne, FL WSR-88D to the KSC. Range rings every 10 km are depicted. The LDAR central site is located just less than 50 km north of the radar site.

The WSR-88D operates in two modes: clear-air mode and precipitation mode. When the radar is operating in precipitation mode there are two VCP's that are used: VCP-21 and VCP-11. A radar volume created in VCP-21 mode is made up of scans at nine elevations ( $0.5^\circ$ ,  $1.45^\circ$ ,  $2.4^\circ$ ,  $3.35^\circ$ ,  $4.3^\circ$ ,  $6.0^\circ$ ,  $9.9^\circ$ ,  $14.6^\circ$ , and  $19.5^\circ$ ) and is accomplished in about six minutes. VCP-11 mode provides scans at fourteen elevation levels ( $0.5^\circ$ ,  $1.45^\circ$ ,  $2.4^\circ$ ,  $3.35^\circ$ ,  $4.3^\circ$ ,  $5.25^\circ$ ,  $6.2^\circ$ ,  $7.5^\circ$ ,  $8.7^\circ$ ,  $10.0^\circ$ ,  $12.0^\circ$ ,  $14.0^\circ$ ,  $16.7^\circ$ , and  $19.5^\circ$ ) and is completed in about five minutes. Figure 5 shows the coverage provided by

the two precipitation mode VCP's. The 50 km range line is in bold to serve as a reference to the coverage south and north of the LDAR central site.



**Figure 5. Radar coverage provided by VCP-11 and VCP-21.** These images show the coverage provided by the two precipitation-mode VCP's provided by the WSR-88D. The gray areas represent areas of coverage and the white regions represent areas with no coverage.

Figure 5 reveals that south of the LDAR central site there is very sparse coverage at higher altitudes. In fact, just 20 km south of the LDAR site, there is no radar coverage above 10 km and very limited coverage above 6 km; this limitation in radar coverage is very significant since Boccippio et al. (2001) found that the majority of LDAR data points occur at about 9 km above the ground. It is also clear that north of the LDAR site, much better radar coverage of the upper troposphere is provided by VCP-11 than by VCP-21. However, even with this improved data coverage, there are gaps in the radar coverage at higher elevations.

### **III. Research Methodology**

This section chronicles the procedures that were followed and the logic employed to process the raw LDAR data points into lightning flashes, transpose WSR-88D archive Level II data to a 3D grid of radar reflectivity factor values, and to then merge these two data sets to extract meaningful data about the radar signatures of LDAR data points. As mentioned earlier, this project is one of three current projects being researched by students at AFIT. More than four years of LDAR data were processed, though only ten days of lightning and radar data are used for this particular study. This section also outlines how days were selected for the case studies.

#### **3.1. LDAR Data Point Flash Grouping**

The first task to be accomplished before any of the three AFIT projects could be undertaken was to group the LDAR data points—which essentially represent the locations of the stepped leaders in a lightning channel—into individual lightning flashes. More than 330 million LDAR data points had to be grouped into lightning flashes. An extensive amount of computing time was required to process the massive amount of raw LDAR data into LDAR flash-grouped files. The largest day in the data set consisted of over eight million individual data points; the program ran for almost two weeks to process that day’s lightning activity where more than 120,000 flashes were identified.

The flash-grouping algorithm used by NASA and described by Murphy et al. (2000) was used as the model for grouping individual LDAR data points into lightning flashes. NASA’s flash-grouping routines—which are, at the time of this publication, available on the NASA public web site—are written in the C programming language.



This code was closely examined and used as a blueprint for the flash-grouping algorithm employed in this and the two concurrent studies at AFIT (NASA 2001). Appendix A shows the code of the AFIT flash-grouping program written for the Interactive Data Language (IDL) environment. The algorithm groups LDAR data points into flashes based upon the same spatial and essentially the same temporal constraints as the NASA algorithm.

The raw LDAR data files are ASCII text files that contain timing and location information; the time is recorded to the microsecond and the location of the event is given, in meters, north/south [x], east/west [y], and height [z] above ground level on a flat plane tangent to the LDAR central site. Data points from a calibration signal used to ensure proper synchronization of the system are included in the LDAR data files and are easily removed by the flash-grouping program. The location of this signal is known to within meters, so a simple filter is employed to remove any signal from the region immediately around the calibration signal's source. Once this calibration noise is removed from the data set, the examination of the remaining data points begins.

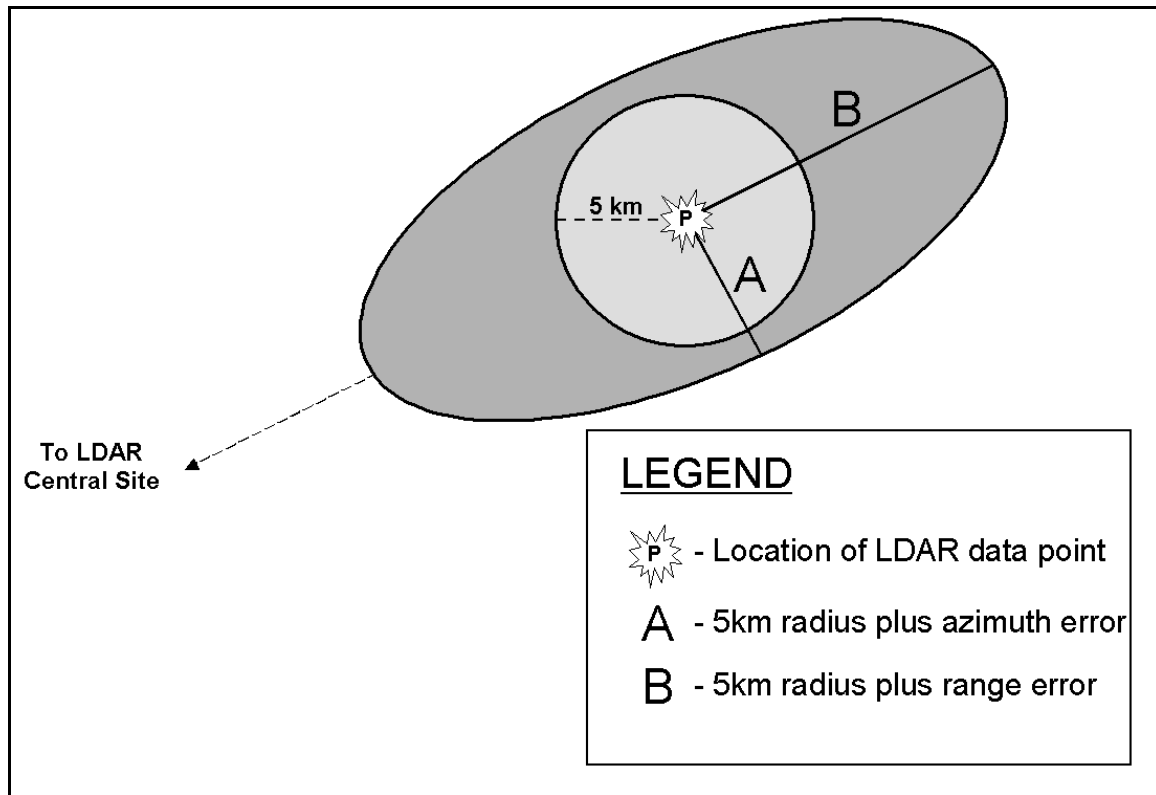
The algorithm determines the following information about each point in an LDAR data file: the line number, flash number, branch number, branch index number, and the parent point. The line number is simply determined by sequentially numbering each data point in the file and is used to identify a point. The flash number identifies all the points that are part of the same lightning flash; LDAR data points that don't meet the spatial and temporal constraints are given a flash number of negative one which indicates that these points are not part of any lightning flash. The branch number identifies points that are determined to be part of the same branch in a lightning flash. The branch index number

indicates the point's sequential position in a branch. Also, the first point in a branch is given a parent point number that corresponds to the line number of the point in the flash that is closest to this first point in a new branch. By saving the preceding information for each point in an LDAR data file, each lightning flash can be reconstructed without any further processing.

To identify the data points that are part of a lightning flash, the first point in the LDAR file that does not have a flash number yet assigned is tentatively considered to be the origin point of the next flash. All LDAR data points that occur within the next three seconds of this potential flash origin point, that have not been identified as part of a previous flash, are examined to determine if they are part of this new flash. The basic spatial criterion for flash grouping is 5 km. Due to the LDAR location errors described in Chapter 2, this 5-km radius is expanded into an ellipse to account for the range and azimuth errors in locating data points as shown in Figure 6. When examining a point to see if it is part of the current flash, all points already identified as part of the current flash are checked to determine if any of those points fall within this ellipse. If any points in the current flash do fall in this region, then the point has met the spatial criteria to be considered part of the current flash.

When a point has met the spatial criteria to be included in a flash, the difference in the end time of the flash—which originally is the time of the origin point and is later updated each time a point is added, since the LDAR data are in time sequence order—and the time of the point is checked. If there is more than a 0.5 second difference between the time of the point being checked and the flash end time, the point is considered to be too far outside the time constraints and the flash is considered terminated. It is clear that

multiple lightning flashes can (and do) occur at the same time in different regions around the LDAR system; fortunately, LDAR is capable of identifying points from simultaneous flashes in multiple locations. This half-second constraint allows for points that might be missed from one lightning flash when there is a virtually simultaneous flash elsewhere.



**Figure 6. LDAR Flash Grouping Ellipse Diagram.** This picture shows the 5 km radius used as the spatial criterion for flash grouping and the orientation of the ellipse around the LDAR data point (p). The semi-minor axis (A) is oriented perpendicular to a line connecting the point p to the LDAR central site. The length of this axis is the 5 km radius plus a one-degree azimuthal error. The semi-major axis (B) represents the 5 km radius plus a range location error factor and is oriented along the line connecting point p to the LDAR central site.

The flashes identified by the program are further grouped into branches of lightning again using a spatial and temporal test. The basic spatial proximity for a point to be considered part of an existing branch is that the point be within 1km of the endpoint

of an existing branch in this flash—beyond a 40 km range from the LDAR central site, this 1-km radius is expanded to account for location errors. The time constraint on including a point in a branch is 0.03 seconds from the end time of the branch. If a point is found to meet both the spatial and temporal constraints to be included in an existing branch, the branch number of the point is set, the point is assigned the next branch index number, and the end point and end time for this branch is updated with this new branch point's information. If a point does not meet the temporal and distance constraints, it is considered to be the first point in a new branch; the nearest point in the flash to this point is then designated the parent point of this new branch.

If a flash is found that contains only one or two points, it is not considered to be a valid flash. The flash number of the origin point of this incomplete flash is set to negative one, while the other points in the incomplete flash are reset to allow consideration for inclusion in another flash. Since the LDAR data files are ordered sequentially by time, the process described here simply repeats until all points have either been grouped into flashes or found to be incoherent noise. After the program executes, the output is saved to a text file. These output files include all of the original data from the valid—non-calibration—LDAR data points for each day, plus the flash and branch information described above. Once the LDAR flash files were processed, the next step was to select days for the case study.

### **3.2. Case Study Selection**

The nature of working with archived radar data makes it impractical—if not utterly impossible—to merge several years of lightning data with radar data. Therefore, the intent was to select several days of thunderstorm activity near the KSC, preferably

while experiencing the influence of a variety of weather regimes. The possibility of examining lightning and radar data while the KSC area was under the influence of either a tropical storm or hurricane was examined, but no available days of the LDAR activity could be associated with the archived tracks of tropical storms. So, two types of weather making conditions were selected for case studies: synoptic and airmass.

**3.2.1. Synoptic Cases.** The term synoptic in this context is used to describe days where the thunderstorm activity in the KSC area is caused primarily by the passage of a synoptic-scale weather system such as a mid-latitude cold front that extends down to the Florida peninsula. The Bermuda high normally dominates during the summer months and prevents most cold fronts from reaching central Florida intact. In the late-winter and early-spring months, however, cold fronts do tend to influence the weather in Florida and are one of the major weather producers during this time. The methodology used to determine potential days for case study of synoptic cases involved examining the size of LDAR flash grouped data files and national radar mosaic images.

LDAR data files from 1997 through the summer of 2001 that were processed with the flash-grouping algorithm (see Appendix A) were sorted by size. The file naming convention used for the LDAR flash-grouped files allowed easy identification of the date of the file. Days with a large file size—indicating a great deal of lightning activity around the KSC—that occurred in the late-winter/early-spring were noted. Next, national radar mosaic images, archived on the NCDC web site, were examined to look for signatures of either a squall line or a cold front moving through the KSC area on the days of significant LDAR activity. One synoptic day from each year of available data was then selected. Table 1 shows quantitative data for the five synoptic days that were

chosen. The number of non-calibration LDAR data points and the number of lightning flashes identified by the flash-grouping algorithm for each day are shown. The average number of LDAR data points per lightning flash for each day is also included. It should be noted that data included in this table cover the entire day and not just the time when thunderstorm activity was in the immediate KSC area. For these five days, the flash-grouping program processed more than 288,000 lightning flashes, consisting of more than 17 million data points. This equates to an average flash rate over the entire domain of the LDAR network of about 40 flashes per minute, which was sustained for 120 hours. The extremely large influence of 23 April 1997, where the flash rate is 89 flashes per minute over the 24-hour period, must be taken into account, however. The other four days yield an average flash rate of almost 28 flashes per minute.

**Table 1. Total LDAR Flash Activity on Chosen Synoptic Days.**

<b>Synoptic Days</b>			
<b>Date</b>	<b>Number of LDAR Points</b>	<b>Number of Flashes</b>	<b>Mean Points/Flash</b>
April 23, 1997	8,021,236	128,392	62.5
February 23, 1998	2,736,158	45,500	60.1
February 28, 1999	556,190	10,439	53.3
March 31, 2000	2,965,290	26,673	111.2
March 29, 2001	3,429,607	77,238	44.4
<b>Totals</b>	17,708,481	288,242	61.4

**3.2.2. Airmass Cases.** There were many more LDAR data files that indicated significant lightning activity in the summer months and that would have potentially been good choices for inclusion in the airmass cases. Most late-spring to late-fall days in central Florida have a good chance of airmass thunderstorm development; the area around the KSC is known as lightning alley for this very reason. The larger pool of days

with significant LDAR activity in the summer time frame made it more difficult to pick days for the airmass cases. Again, the national radar mosaics were examined, but it was much more difficult to identify exactly where the thunderstorms were occurring in relation to the KSC; the lack of linear radar echo features—such as was normally present in the synoptic events—made the selection process for the airmass days much harder.

Table 2 shows the LDAR activity for the five chosen airmass case study days. Again, the data here are for the entire day and not just when thunderstorms were occurring in the immediate KSC area. The flash-grouping algorithm grouped more than 160,000 flashes, which were made up of more than 11 million data points, for these five days. The average number of LDAR data points per lightning flash is about 71, compared to an average of about 61 for the synoptic days. Similarly, the average flash rate over the five-day period—and over the entire LDAR network range—is about 22 flashes per minute; this is significantly less than the 40 flashes per minute noted in the synoptic cases, but not that much different than the flash rate of about 28 flashes per minute for the synoptic cases when the 23 April 1997 influence is accounted for.

**Table 2. Total LDAR Activity on Chosen Airmass Days.**

<b>Airmass Days</b>			
<b>Date</b>	<b>Number of LDAR Points</b>	<b>Number of Flashes</b>	<b>Mean Points/Flash</b>
August 3, 1997	2,275,840	24,071	94.5
July 6, 1998	3,901,975	48,235	80.9
June 11, 1999	2,749,853	27,121	101.4
July 7, 2000	2,201,607	40,012	55.0
June 15, 2001	606,171	25,003	24.2
<b>Totals</b>	11,735,446	164,442	71.4

### **3.3. Radar Data Processing**

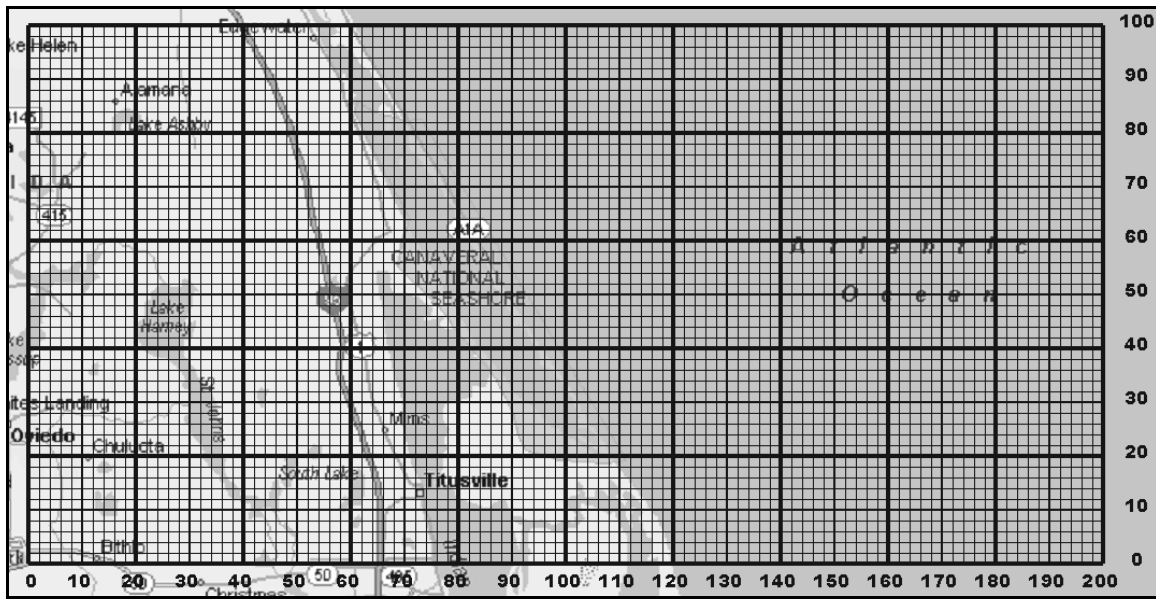
Once the case study days were chosen, the radar data for each identified day were ordered from NCDC through the Air Force Combat Climatology Center. The WSR-88D archive Level II data arrived on 8mm data tape. The National Center for Atmospheric Research (NCAR), Mesoscale and Microscale Meteorology (MMM) Division, developed software that can translate this WSR-88D archive Level II radar data to a 3D Cartesian grid of reflectivity values.

**3.3.1. Translation to 3D Grid.** The Sorted Position Radar Interpolation (SPRINT) program was used to process the WSR-88D archive Level II data files. SPRINT creates a 3D data set of floating-point radar reflectivity factor (in dBZ) values by converting reflectivity data stored in azimuth, range, and elevation angle format in the NCDC archive Level II files to a 3D Cartesian grid of reflectivity. A standard atmosphere—using a 4/3 effective earth radius approximation—is used by SPRINT to determine the height above ground level as the beam propagates away from the radar site. Defining the size and resolution of the grid is the critical step in processing the archived radar data.

The 3D grid that was defined has 201 points in the x-direction (east/west), 101 grid points in the y-direction (north/south), and 34 layers in the vertical, with a horizontal and vertical resolution of 500 m. The [x,y] grid location closest to the LDAR central site is [100,0]. The LDAR central site is located about 1.13 km east, and 47.32 km north, of the WSR-88D location. SPRINT does not allow the exact positioning of the grid to this precision, so the actual position of the [100,0] grid point is 47.5 km north, and 1.0 km east, of the radar; the grid point [100,0] is therefore about 222 m northwest of the LDAR



central site. The grid covers an area of 20,000 km<sup>2</sup> and extends 50 km west, north, and east of the LDAR central site. The grid also provided coverage from 500 m above ground level to 17km in the vertical. This equates to a volume of 340,000 km<sup>3</sup> with 690,234 data points. A planar view of this radar grid over a map background is shown in Figure 7.



**Figure 7. Planar View of Radar Grid.** There are 201 points in the x-direction and 101 points in the y-direction. The LDAR central site is located just southwest of the point [100,0]. The lines shown are drawn every kilometer, but the actual resolution of the grid is 500 m. Not depicted in this 2-dimensional drawing is the 34 layers in the vertical that also provide a 500 m resolution from 500 m to 17 km altitude.

The limits of the radar coverage at higher altitudes provided by the two WSR-88D precipitation modes (VCP21 and VCP11) south of the LDAR central site were the primary factor considered when the grid was defined. Having the grid only extend to the north of the LDAR central site ensures better coverage from the surface to 17 km (about 55 Kft). SPRINT restricts the number of data points that can be included in the Cartesian reflectivity grids it creates, which was the major reason for the choice of a 500 m grid

resolution. The output data files created by SPRINT are saved in a format that can essentially only be read by another program developed by NCAR/MMM.

The Custom Editing and Display of Reduced Information in Cartesian space (CEDRIC) program was used to translate the SPRINT output files to a more useful format. One of the CEDRIC options is to convert SPRINT binary output data files to Network Common Data Format (NetCDF) files. NASA and the Unidata program at the University Corporation for Atmospheric Research jointly developed the NetCDF as a standard way of storing and sharing scientific information. IDL has built-in routines that allow easy access to data structures stored in NetCDF. With these IDL routines, the 3D grid of reflectivity values can easily be read into a 3D array of floating point numbers. In addition to the reflectivity information, the start and end time of the radar volume can easily be extracted from these NetCDF files.

The 3D array of dBZ values created by SPRINT/CEDRIC is then used to create a 2D array of composite reflectivity. Any mention in this study to the *base reflectivity* of a point refers to the 3D reflectivity array, and references to *composite reflectivity* refer to the 2D data set. To create the composite reflectivity array, the maximum base reflectivity value in the vertical column for each [x,y] location is assigned as the composite reflectivity value for that [x,y] grid point.

To ensure that the radar volumes created with this process were valid, sample base and composite reflectivity images were verified by comparing planar and 3D views of the SPRINT/CEDRIC processed data with planar views of composite and base reflectivity created using the WSR-88D Algorithm Testing and Display System (WATADS) software. The images confirmed that the interpolation to the 3D grid was

indeed successful; landmark and radar signature correlation was very good. There were, however, problems encountered when running SPRINT and there were also some data quality issues identified when looking at some of the 3D radar volumes.

**3.3.2. Efficiency and Radar Processing Issues.** In order to process the WSR-88D archive Level II data, the data files first had to be dumped from the 8-mm data tape to a hard drive storage device. To run the SPRINT program, a script file was created that defined the location and resolution of the desired 3D grid of reflectivity values. SPRINT execution was quite fast; it normally took less than 30 seconds to process a radar volume. The CEDRIC program ran even faster, normally completing execution in only a few seconds per radar volume. A script file to allow the processing of multiple radar volumes consecutively with one call to the SPRINT executable was created. It would appear to complete execution normally. A companion script file to convert the multiple files created by the SPRINT run to NetCDF file format with a single call to CEDRIC was created. Upon execution of this script, however, a problem soon became evident.

Not all of the WSR-88D source radar volume files were being processed by SPRINT. SPRINT would periodically encounter a situation where, for an unknown reason, it was unable to match the volume scan data to the 3D grid; when this problem occurs, SPRINT would simply not create an output file for that volume and would attempt to process the remaining source radar volume files. When the CEDRIC script file tried to access the SPRINT output files, there would be missing input files and CEDRIC would halt and cause a core dump. Eventually, all radar volumes were processed, one file at a time; this became a very tedious procedure.

While processing the raw radar volumes with SPRINT, an inventory of radar volumes that SPRINT was unable to process was kept. In fact, 14% of the source radar volume files (73 out of 523) could not be processed by SPRINT. No determination of what was causing the malfunction could be identified. The source radar volumes were processed and viewed with WATADS to check for data gaps or missing elevation levels, and no such problems with the source data could be found. Later, another problem with the SPRINT processing was discovered when viewing the 3D radar volumes using IDL's object-oriented graphics rendering capabilities.

Eventually, all 450 radar volume files that were successfully processed—at least those not causing an error—by SPRINT were visually examined. Of these files, 42 were found to have no meaningful radar echoes; this doesn't mean that the data was bad, rather that these volumes were for inactive periods where there was no lightning activity. This leaves 408 radar volume files that SPRINT processed and CEDRIC translated without causing an error. However, visual inspection of all 408 radar volumes found that 27% of these files—111 of the 408—had significant sections of data missing that would make even a composite reflectivity computation unreliable—73% of the files were, at least, partially usable. These 111 volumes were deemed unusable and were excluded from use for any reflectivity or distance computations. For a graphic example of this type of error, see Figure 16 in Appendix B.

Of the 297 remaining radar volume files, about 70% were found to be fully usable and were used for both composite and base reflectivity calculations, and distance computations. The other 30% were subjectively deemed to be partially usable radar volumes. Partially usable radar volumes were complete enough that an accurate

composite reflectivity image grid could reasonably be created from the 3D reflectivity grid, but too much data were missing for reliable base reflectivity and distance determination. Figure 17 in Appendix B is an example of a partially usable radar volume.

### 3.4. Merging LDAR and Radar Data

Once the 2D and 3D arrays of reflectivity were created, it was possible to merge the radar and lightning data sets. Since the relative location of the LDAR central site to the point [100,0] in the reflectivity grids is known, a simple coordinate transformation is all that is required to convert the LDAR data point location to the radar reflectivity grid. The equations used for this coordinate transform are as follows:

$$x = 100 + ((flash.x + 130) / 500) \quad (2)$$

$$y = (flash.y - 180) / 500 \quad (3)$$

$$z = (flash.z - 500) / 500 \quad (4)$$

where the x, y, and z location of the LDAR data point (in meters) is denoted by *flash.x*, *flash.y*, and *flash.z* respectively. The result of these equations is the x, y, and z grid location of the LDAR data point relative to the 3D base reflectivity grid—or the 2D composite reflectivity grid if only the x and y locations are considered. This location will normally not fall exactly on a grid point, so optimal interpolation is used to determine the radar reflectivity factor for each LDAR data point in a lightning flash. In an effort to provide aircrew members with relevant guidance based upon what they can expect to observe on their radar displays, the distances from LDAR data points to critical reflectivity thresholds are examined. The procedures used to calculate this information are detailed in this section.

3.4.1. **Determining Reflectivity.** To determine the radar reflectivity for the points in LDAR flashes, the LDAR flash data file for the day being examined is opened and all data is read into an array of data structures with the timing, location, and flash/branch information for each data point. The first radar volume file to be merged with the lightning data is opened. A 3D base reflectivity array and a 2D composite reflectivity array are created as described earlier, and the start time and end time of the radar volume are extracted from the NetCDF radar volume file. Only lightning flashes that occur in the proper time window and whose points are all within the radar reflectivity grid are considered.

The LDAR data array is searched to identify the flash origin points that are within the time window of the radar volume and that are located within the 100 km by 50 km radar grid. Once the flash origins are identified, each flash whose origin point is within the grid is checked to see if all points in the flash are, too, entirely within the confines of the radar grid. Once the flashes that meet the time and space criteria are identified, the individual data points of each flash are examined to determine the radar reflectivity factor by using the coordinate transformation equations and optimal interpolation. Both the 3D base and the 2D composite reflectivity for each data point are calculated. This process continues for all of the identified flashes that occur within the temporal bounds of the radar volume NetCDF file—normally a span of five to six minutes.

The next radar volume file is then opened and the process repeats until all radar volumes have been examined. The time window of the subsequent radar volumes is taken from the end time of the previous radar volume scan to the end time of the current radar volume scan to avoid missing any flashes that originate during the slight delay

between radar volume times. If there are missing radar volume scans, which there commonly are due to the problems with the SPRINT interpretation of some radar volumes, the start and end time of the volume is once again used and some of the lightning data is skipped since there is no corresponding radar data.

For each radar volume scan, a new lightning data file is created and saved with all the timing, location, flash/branch information from the LDAR flash file, plus the reflectivity—both 3D base and 2D composite—data all the points in the flashes that occur within the time and space constraints for the radar volume. Saving the data for these five to six minute windows, and with a much smaller spatial region, greatly reduces the individual data file size and increases the speed of processing the data for subsequent analysis. The reflectivity data files that are saved during this step can be directly compared with the associated radar volume to determine the distances of these LDAR data points from significant radar echoes.

**3.4.2. Determining Distances from Radar Echoes.** The radar display on the Air Force's C-17 aircraft shows radar echoes with a three-color scheme. Radar echoes greater than or equal to 40 dBZ are displayed in red, while reflectivity values between 30 and 40 dBZ are portrayed in yellow, and 20 to 30 dBZ echoes are shown in green (Lorenz 2001). Since the C-17 only displays reflectivity data in three colors, the 40-dBZ threshold was chosen as the best reflectivity value to represent the reflectivity core of the thunderstorm cells that lightning distances should be measured from. Interestingly, Gremillion and Orville (1999) identified a possible relationship between the detection of the 40-dBZ echo at the level of the  $-10^{\circ}$  C temperature and CG lightning initiation in airmass thunderstorms near the KSC. Hoffert and Pearce (1996) also noted that most

LDAR activity was initiated directly above the reflectivity cores in the thunderstorms around the KSC that they investigated—although they identified the reflectivity core as being above 30 dBZ. As such, the distances to be measured will be from the nearest 40-dBZ threshold of reflectivity.

An IDL program was written to calculate the distance of LDAR data points from these radar echo cores. The program opens a NetCDF radar volume file to extract the 3D base reflectivity volume and the corresponding LDAR flash reflectivity file with the lightning flash data points. The reflectivity at each grid point in the 3D radar array is rounded to the nearest integer dBZ value to aid in identifying the location of the threshold between the yellow (30 – 40 dBZ) region of a C-17 display and the red (40 dBZ or higher) echo. A 2D composite reflectivity grid is then created from this modified 3D base reflectivity volume.

All points in the base and composite reflectivity arrays with a radar reflectivity value greater than or equal to 40 dBZ are identified and the grid locations of these points are stored in an array. The points in both the base and composite reflectivity arrays that have radar reflectivity values of between 30 – 39 dBZ are identified as well. Again, these thresholds correspond to the red and yellow displays of the C-17 radar, respectively, but would also correspond to a WSR-88D 40-dBZ threshold on a composite reflectivity display. With the locations of these critical radar data points saved in appropriate arrays, the distance to the nearest of these points from any LDAR data point can be calculated. Recall that the LDAR data files used by this program contain only flashes that occur entirely within the corresponding radar volume—based upon spatial and temporal constraints. These data files have all the original LDAR data (time and position data),



plus the flash grouping data (flash number, etc.), as well as the radar reflectivity data (base and composite). For each LDAR data point, two distances are calculated.

The first distance is the horizontal distance from the LDAR data point's [x,y] location to the edge of the nearest 40-dBZ composite reflectivity threshold (the red/yellow line on a C-17 radar display). If the LDAR data point has a composite reflectivity value greater than or equal to 40 dBZ, the distance is calculated, in meters, to the nearest radar grid point with a radar reflectivity of between 30 – 39 dBZ (yellow on the C-17 display). This distance indicates how far the point is inside the red radar echo, as displayed by the C-17 radar. If the LDAR data point has a composite reflectivity value of less than 40 dBZ, the horizontal distance to the nearest composite reflectivity grid point of 40 dBZ or higher is calculated. By convention, any distance that represents how far an LDAR data point is inside a given radar reflectivity threshold is considered to be a negative distance; a positive distance, therefore, indicates how far outside of a reflectivity threshold a point is.

The second distance that is measured is a 3D distance, in meters, from the LDAR data point's [x,y,z] location to the nearest red/yellow threshold as would be displayed by the C-17 radar. Here, if a point has a base reflectivity of greater than 40 dBZ, the distance to the nearest 3D radar grid location with a reflectivity of between 30 – 39 dBZ is calculated, and interpreted as a negative value. For LDAR points with a base reflectivity of less than 40 dBZ, the distance to the nearest 40 dBZ or higher base reflectivity location is calculated. This effectively measures the distance from each point in the LDAR reflectivity data file to the nearest 40-dBZ line on a radar display. One additional constraint is placed upon flashes to be considered for the base reflectivity

computations, if the flash origin reflectivity value has a value of less than zero (dBZ), the flash is ignored. The reason for this constraint is to eliminate the influence of bad data points left over from the SPRINT interpolation. SPRINT assigns a reflectivity of  $-32768$  to indicate bad data. Radar volumes that were marginal as far as the subjective analysis of whether or not a volume was usable tend to have numerous LDAR data points that return a reflectivity value of  $-32768$ . The conservative approach that if a flash origin is being influenced by corrupt (or missing, due to the gaps in the particular VCP) data, then any inference about distances would be suspect. In addition, if more than 25% of the points in a flash were bad data, no base reflectivity based distance calculations were accomplished, again to avoid data corruption.

The net result of this constraint, combined with the elimination of the 27% of the processed radar volumes that were too corrupt to reliably determine any base reflectivity distance calculations, is that the final sample size of the base reflectivity dataset is much smaller than the final composite reflectivity dataset. Table 3 shows the breakdown of the lightning activity for the 297 radar volumes that are being processed for composite reflectivity calculations. These radar volumes cover a time span of approximately 25 hours of thunderstorm activity; this equates to a sustained flash rate—only within the spatial confines of the defined radar grid—of about 13 flashes per minute.

Table 4 shows the same information for the limited data set that is being considered for base reflectivity computations. The 209 radar volumes that were deemed usable for base reflectivity considerations correspond to about 18 hours of thunderstorm activity. The 8,515 lightning flashes with both the origin point and at least 75% of all points that are not influenced by bad radar data represents a sustained flash rate of about

eight flashes per minute within the bounds of the 3D radar volume coverage. The next section presents the findings resulting from the processing of these datasets.

**Table 3. Final Dataset for Composite Reflectivity Calculations.**

<b>Date</b>	<b>Number of LDAR Points</b>	<b>Number of Flashes</b>	<b>Mean Points/Flash</b>
April 23, 1997	239,277	1,634	146.4
August 3, 1997	128,394	1,156	111.1
February 23, 1998	187,658	2,549	73.6
July 6, 1998	154,971	1,165	133.0
February 28, 1999	61,635	201	306.6
June 11, 1999	66,201	656	100.9
March 31, 2000	295,367	1,640	180.1
July 7, 2000	222,439	2,361	94.2
March 29, 2001	321,672	3,043	105.7
June 15, 2001	184,883	5,218	35.4
<b>Totals</b>	<b>1,862,497</b>	<b>19,623</b>	<b>94.9</b>

**Table 4. Final Dataset for Base Reflectivity Calculations.**

<b>Date</b>	<b>Number of LDAR Points</b>	<b>Number of Flashes</b>	<b>Mean Points/Flash</b>
April 23, 1997	92,989	585	159.0
August 3, 1997	7,708	37	208.3
February 23, 1998	92,432	1,152	80.2
July 6, 1998	71,140	499	142.6
February 28, 1999	25,282	76	332.7
June 11, 1999	43,255	415	104.2
March 31, 2000	146,637	771	190.2
July 7, 2000	80,597	917	87.9
March 29, 2001	209,196	2,010	104.1
June 15, 2001	69,968	2,053	34.1
<b>Totals</b>	<b>839,204</b>	<b>8,515</b>	<b>98.6</b>

## **IV. Results and Analysis**

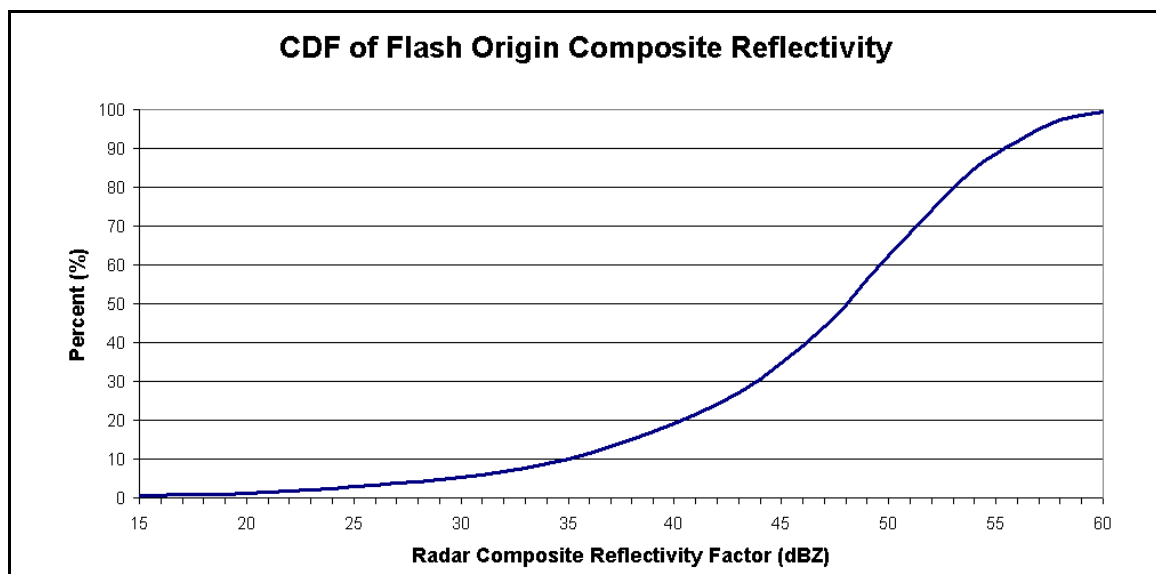
### **4.1. Flash Origin Radar Characteristics**

Determining the characteristic traits of lightning flash origin points is approached from two different ways. The first is to look at the composite reflectivity signature of the LDAR flash origin points with a focus on the requirements for Air Force weather personnel to make decisions about the issuance, or cancellation, of lightning warnings. The second strategy involves focusing on the 3D radar reflectivity environment around these lightning flash origins. Using the results from this 3D reflectivity analysis, better insight into the radar characteristics of lightning flash origins are possible. An understanding of these flash origin radar traits may facilitate making aircrew members more aware of the expected lightning threat area when flying near thunderstorms.

**4.1.1. Composite Reflectivity.** Gremillion and Orville (1999), and Hoffert and Pearce (1996), suggest that lightning flash origin points are normally located above the main reflectivity core or hail shaft. The mean composite reflectivity of these lightning flash origins should, in theory, be fairly high. Therefore, we would expect to find that most flash origins are either found within the 40-dBZ composite reflectivity return, or, at the least, they should be very close to the composite reflectivity core—depending upon the threshold used to define the reflectivity core (recall that Hoffert and Pearce used 30 dBZ).

For all of the composite reflectivity results discussed herein, 19,623 lightning flashes—consisting of more than 1.8 million LDAR data points—were merged with 2D composite radar reflectivity data. The mean composite radar reflectivity factor of the flash origin points is 45.8 dBZ. Figure 8 shows the cumulative distribution function

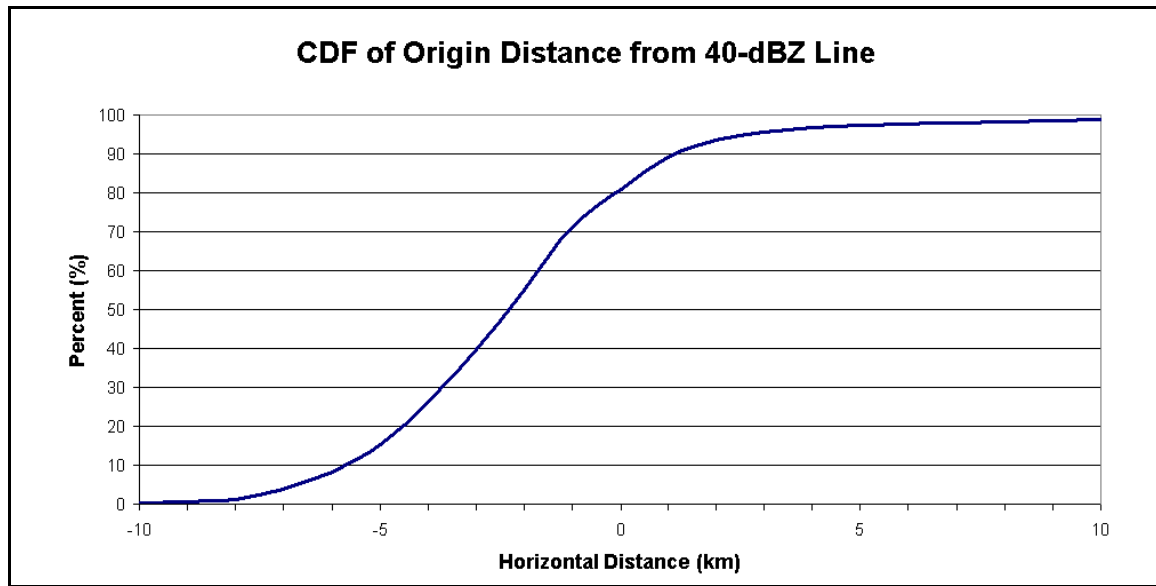
(CDF) for the composite reflectivity of the lightning origin points. The CDF presents the data in a way that makes it easy to determine the meaning of percentiles. For example, it is apparent that more than 80% of all flash origin points had a composite reflectivity of greater than 40 dBZ, and 95% of the origin point have a composite reflectivity of more than 30 dBZ—the lower threshold suggested by Hoffert and Pearce (1996). About 40% of the flash origin points have a composite reflectivity greater than 50-dBZ.



**Figure 8. CDF of Origin Composite Reflectivity.** The cumulative probability of composite radar reflectivity factor (dBZ) for the 19,623 flash origin points is shown here. Examination shows that 95% of all flash origins have a composite reflectivity of greater than 30 dBZ. 90% of all flash origin reflectivities are greater than 35 dBZ, and 80% of the origin points have a reflectivity of greater than 40 dBZ.

For the flash origin points with a composite reflectivity of less than 40 dBZ, just how far are they from the nearest edge of the nearest 40-dBZ echo? Or, for points within the 40-dBZ echo, how far is it to the nearest return that is less than 40 dBZ? The data verify that, indeed, most of the lightning flashes do originate either within, or very close to, the radar reflectivity cores. Figure 9 is the CDF for the horizontal distance—since we’re only looking at 2D, planar, radar composites—from the flash origin point to the

edge of the radar echo that marks the 40-dBZ threshold. For points within the composite reflectivity core, the distance (in kilometers) is indicated as a negative distance, measured to the nearest composite reflectivity value between 30 – 39 dBZ. The mean horizontal distance to the edge of the reflectivity core for this dataset is –2.55 km.



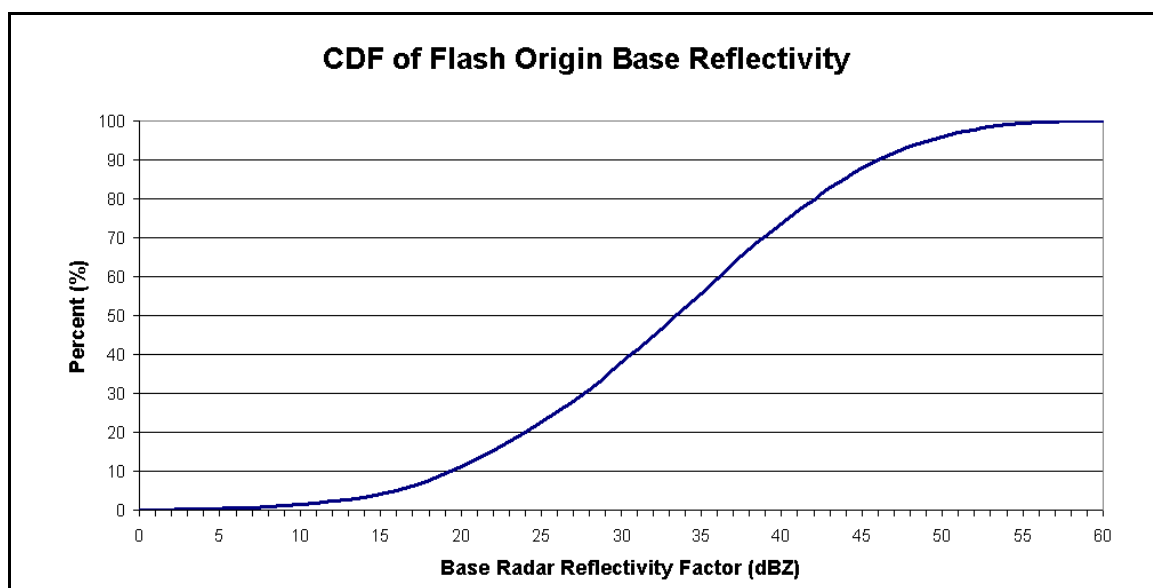
**Figure 9. CDF of Origin Horizontal Distance from 40-dBZ Echo.** This plot validates that 80% of the flash origin points were indeed within the 40-dBZ echo. 90% of all flash origins are either within the 40-dBZ reflectivity core, or are less than 1 km from the outside of the 40-dBZ threshold. In fact, 95% of all flash origin points are within about 3 km (about 1.6 NM) of the of this 40-dBZ echo.

As is expected after analyzing the distribution of flash origin composite reflectivity, the horizontal distance CDF verifies that around 80% of the flash origin points were inside the radar reflectivity core. It is also evident that there is a good agreement between the 40-dBZ threshold and lightning origin locations—with 95% of all origins either within, or no more than 3 km outside of, the composite reflectivity core. This suggests that there may be a potential to use the 40-dBZ line as a critical threshold for determining a rule-of-thumb for lightning warning issuance, or cancellation, criteria.

It is clear that lightning flashes do indeed appear to originate in the vicinity of composite radar reflectivity cores, but what about the actual reflectivity of the flash origin points?

**4.1.2. Base Reflectivity.** As detailed in the previous chapter, the dataset for the base reflectivity analysis is much smaller due to radar volume processing issues and corruption of reflectivity from bad data values in the interpolated radar volumes. 8,515 lightning flashes—made up of 839,204 LDAR data points—were examined to determine the base reflectivity values and distances from radar reflectivity cores. The mean base radar reflectivity factor for the flash origin points is 33.5 dBZ—which is significantly less than the mean composite reflectivity of flash origins of 45.8 dBZ. Figure 10 shows the CDF for the base reflectivity results. Whereas 90% of the flash origin composite reflectivity values were greater than 30 dBZ, for base reflectivity, 90% of the flashes exceed only 20 dBZ—which would correspond to the outermost edge of the green reflectivity displayed by the C-17 radar.

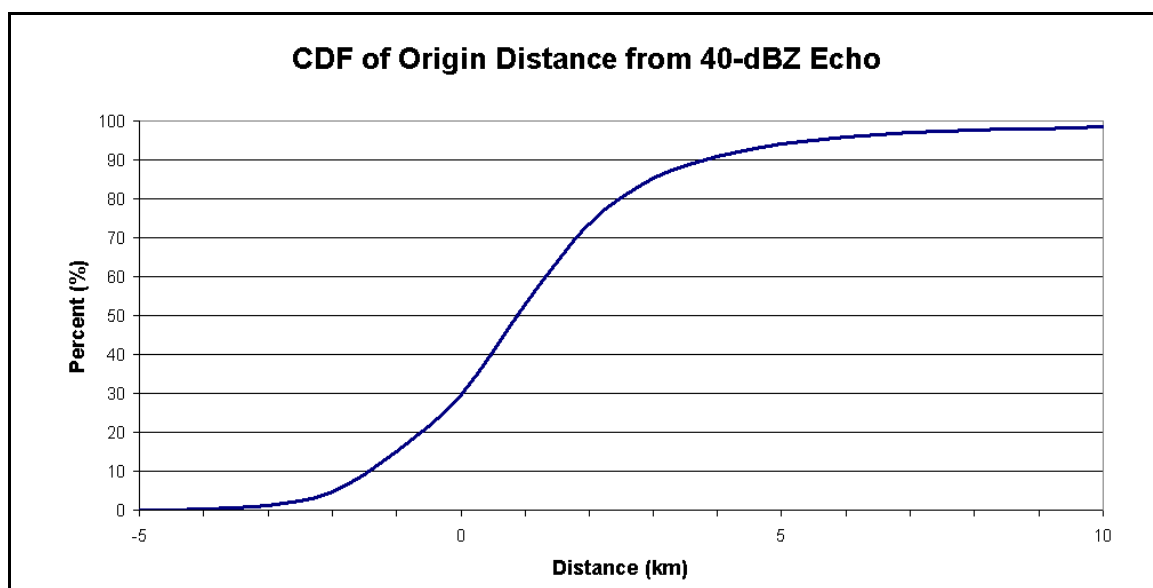
Recall that the composite reflectivity data suggested that the lightning origin points are normally located within the reflectivity core. The base reflectivity data indicates that more often these flash origin points are either within the top portion of the radar reflectivity core, or nearly directly above the reflectivity cores. This is further supported by the fact that Boccippio et al. (2001) found that the majority of LDAR data points tend to be detected at around 9 km (near 30 kft) where one would be expected to find lower base reflectivity values.



**Figure 10. CDF of Flash Origin Base Reflectivity.** The 8,515 flashes considered for base reflectivity indicate that about 90% of all flash origin points have a base (3D) radar reflectivity factor of greater than about 20 dBZ—this would correspond approximately to the outer edge of the C-17’s radar display. Only about 25 – 30% of all flash origin points actually were initiated within the 40-dBZ reflectivity core.

For the C-17 pilot to get better feeling of just where these flashes originate with respect to the radar reflectivity cores, the 3D distance from each flash origin point to the edge of the nearest 40-dBZ base reflectivity echo was calculated. The mean distance from the flash origin to the reflectivity core is +0.8 km (i.e. outside the 40-dBZ core). Figure 11 displays the CDF for flash origin 3D distance from the core echo. 95% of flashes originated within 6km (about 3.2 NM) of the radar reflectivity cores. When combined with information about the extent that flashes tend to travel horizontally from the flash origin, this data could potentially provide insight into thunderstorm avoidance criteria based upon the aircraft’s distance from significant radar echoes. Maximum lightning flash distances from the origin were also computed during the processing of the flash origin data, and will now be discussed.

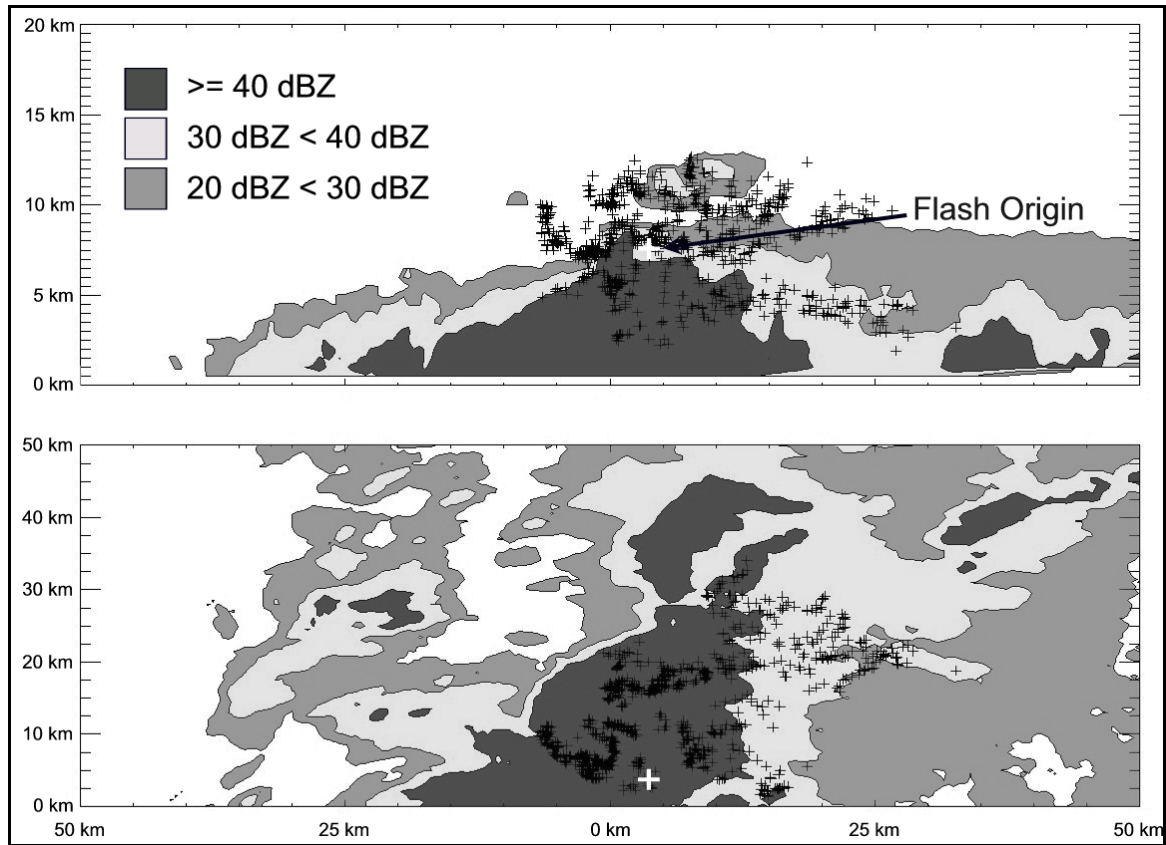




**Figure 11. CDF of Origin Distance from 40-dBZ Echo.** 90% of the 8,515 flash origins examined were located within about 4 km (around 2 NM) of the 40-dBZ radar reflectivity core. The data verifies that about 25% of the flash origins are actually within the 40-dBZ echo. 95% of the flash origin points are less than about 6 km (3.2 NM) from the nearest 40-dBZ echo. (Note: all distances are actual 3D distance, not simply horizontal distance.)

## 4.2. Overall Flash Distances

Hundreds of lightning flashes were plotted over composite reflectivity displays and vertical radar cross-sections and visually inspected. It became evident that most of the lightning flashes did tend to originate near, and normally above, radar reflectivity cores (see Figure 12). Another interesting feature that stood out was that many flashes that branch out a significant horizontal distance from the flash origin, often times tend to almost follow the radar reflectivity contours. With this empirical trend in mind, it seemed fitting to try to encapsulate some basic information about the horizontal extent that lightning flashes travel, not only from the source point, but also from the radar reflectivity cores. A much more thorough survey of this type of data using the entire LDAR dataset at AFIT is currently being completed by Captain David Vollmer.

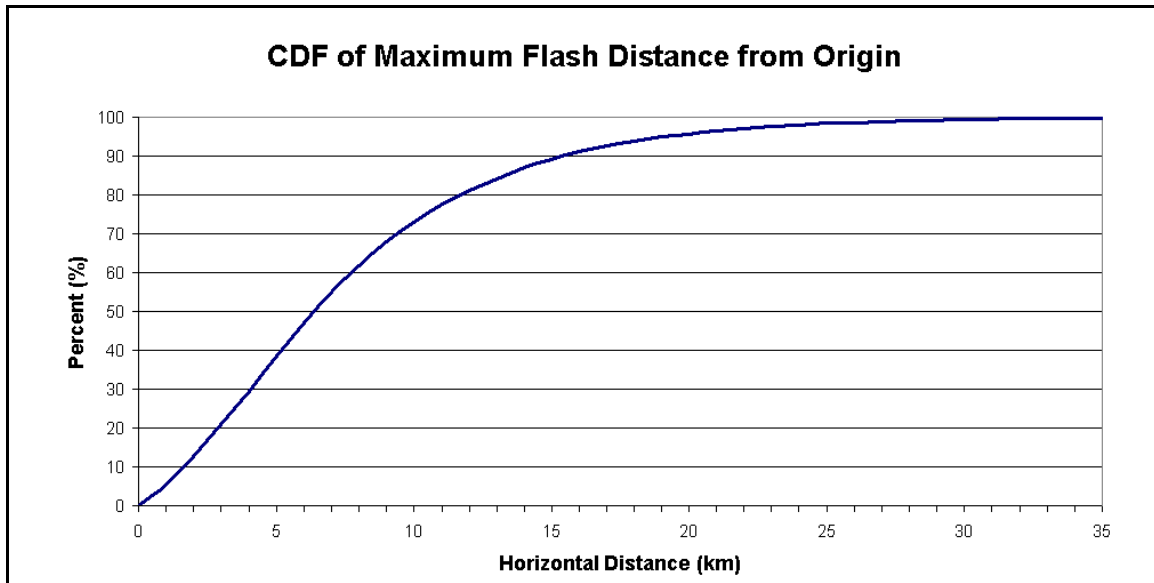


**Figure 12. Vertical and Horizontal Lightning Flash/Composite Reflectivity Image.** The top panel is a vertical composite reflectivity image (using the maximum reflectivity in the y-direction to determine the composite reflectivity for each  $[x, z]$  grid location) with data points from a single lightning flash plotted. The bottom panel is a planar view of composite reflectivity for the same radar volume with the same lightning flash plotted. The large white plus sign in each image indicates the position of the origin of the flash. Note that this origin is within the 40-dBZ echo on the horizontal view, but is above the 40-dBZ core in the vertical image.

**4.2.1. Distance from Flash Origin.** For the basic investigation into how far lightning flashes travel horizontally, the composite reflectivity dataset was used. It must be stated that since the criterion used to process the dataset called for only using flashes whose entire range of points fell wholly within the bounds radar volume, it is possible that flashes that were more expansive were unintentionally excluded from this analysis. Again, refer to Captain Vollmer's thesis for a more detailed analysis of flash distance limits.

For each LDAR data point in a lightning flash, the horizontal distance between the point and the flash origin was computed, and the maximum distance for the flash recorded. Certainly, the actual horizontal breadth of the flashes is much broader than what is presented here; this analysis simply takes the maximum horizontal distance from origin to extreme point—it is entirely possible that the actual flash extent is about double the distances given here. The CDF of the results of this simple analysis is shown in Figure 13. The mean maximum flash distance from the flash origin point is only 7.2 km (about 4 NM), and 90% of the flashes had a maximum horizontal extent of less than 16 km (or 8.6 NM). Indeed, 95% of the flashes in this dataset had a horizontal limit of about 19 km (10.4 NM), and 99% were less than 30 km (about 16.1 NM). The maximum flash distance in these nearly 20,000 flashes was about 46 km (25 NM).

**4.2.2. Distance from 40-dBZ Line.** As mentioned earlier, a subjective analysis carried out while watching animated plots of hundreds of lightning flashes indicated that there seemed to be a trend for the main part of a flash to, in general, follow the areas of high reflectivity. In order to investigate this, the base reflectivity dataset was analyzed to determine the maximum distance from any point in the flash to the nearest radar reflectivity core. Again, the 40-dBZ threshold—inspired by the work of Gremillion and Orville (1999), and made a prudent choice because of the request by the C-17 SPO—is used to represent the radar reflectivity core for distance determinations. The distance here is the point-to-point 3D distance, instead of the horizontal distances in the previous section.

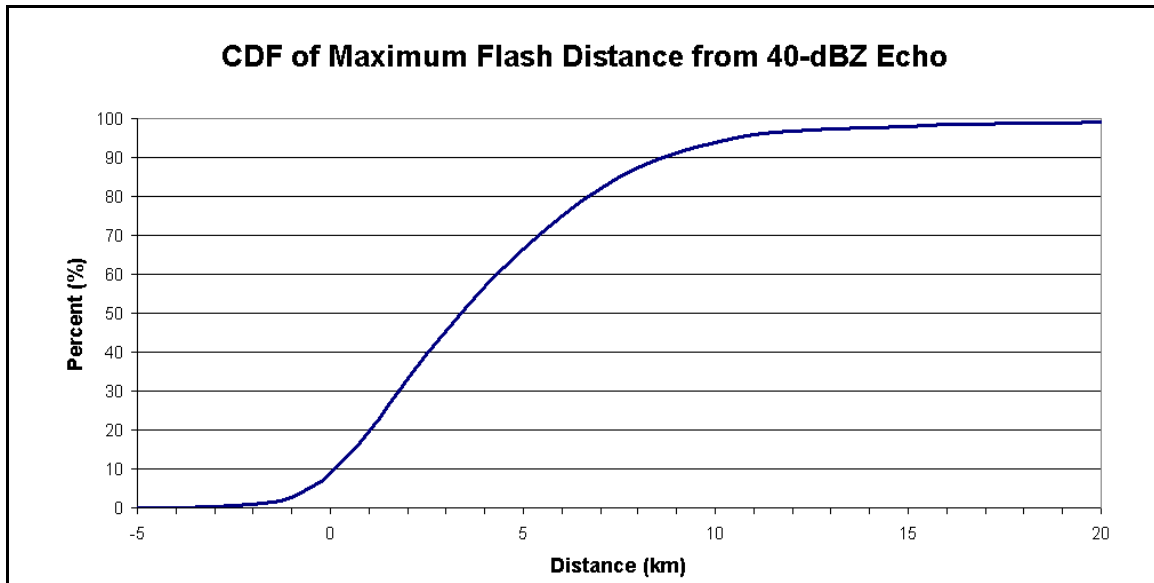


**Figure 13. CDF of Maximum Flash Distance from Origin.** This shows the CDF for the maximum horizontal distance from the flash origin point to the furthest LDAR data point in a lightning flash. 90% of the 19,623 flashes traveled less than about 16 km (8.6 NM) horizontally from the origin point. 95% travel less than around 19 km, and 99% traveled less than 30 km (16.1 NM) from the flash origin.

Figure 14 is the CDF for the maximum flash distance from the 40-dBZ echo. The distances are much less than those found for the overall flash distance. The mean distance from the core echo was 4.7 km (2.5 NM). In contrast to the maximum horizontal distance from the flash origin, where it was found that 99% of all flashes traveled less than about 30 km, the 99<sup>th</sup> percentile for the flash distance from the reflectivity core is only 21 km (11 NM).

#### 4.3. Regime Analysis

The results presented thus far are based upon an analysis of the data for all ten case study days. The composite and base reflectivity data was also analyzed based upon the weather regime: synoptic or airmass. An analysis of the flash origin radar



**Figure 14. CDF of Maximum Flash Distance from 40-dBZ Echo.** This shows the maximum 3D distance that the furthest point from the flash origin traveled from the edge of the 40-dBZ echo. 90% of the 8,515 flashes had a maximum distance from the reflectivity core of less than 9 km (~5 NM), while 95% stayed within about 11 km (6 NM) of the nearest 40-dBZ return. 99% of all flashes had were within about 21 km (11.4 NM).

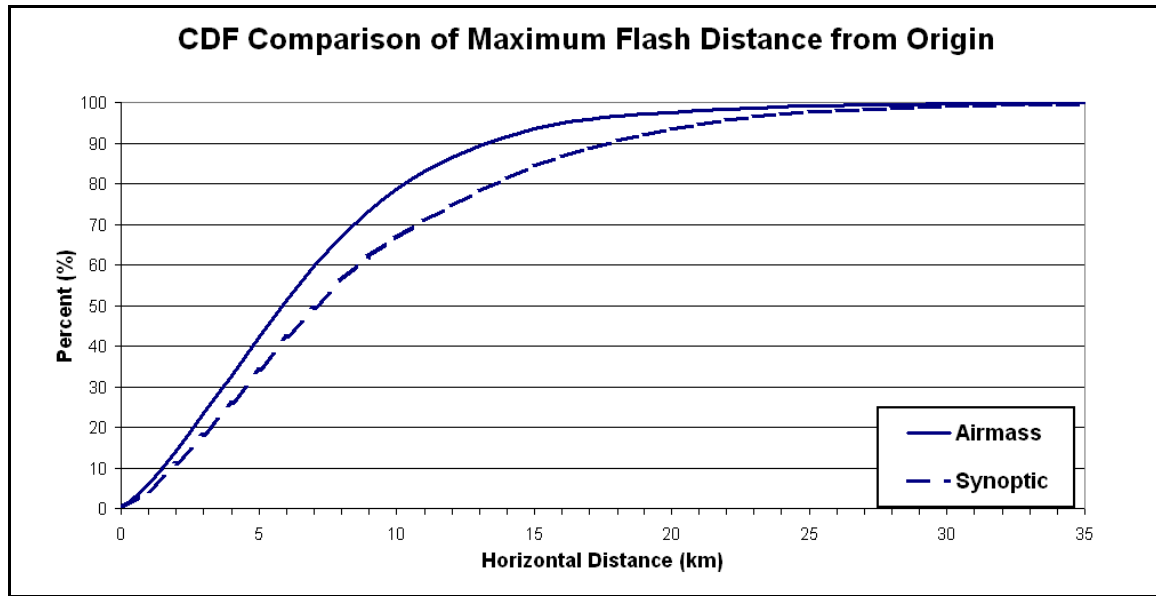
characteristics indicates that none of them displays an operationally significant change between the two regime types. The flash distances, however, do show a change that could potentially impact recommendations for in-flight lightning avoidance.

**4.3.1. Flash Origin Characteristics.** The mean value of flash origin base reflectivity is about 3-dBZ higher for the airmass days than for the synoptic days. There is, however, almost no difference at all in values of the 90<sup>th</sup> and 95<sup>th</sup> percentiles for base reflectivity. For composite reflectivity, the mean reflectivity of the flash origins is less than 1 dBZ higher for the synoptic days than for the airmass days. 95% of all flash origins have a composite reflectivity greater than 27 dBZ for the airmass days, versus 33 dBZ for the synoptic days. A similar difference exists for the 90<sup>th</sup> percentile, with values of composite reflectivity greater than 33 dBZ for the airmass and 37 dBZ for the synoptic

days. To understand the possible operational impact of these variations, the flash origin distance data must also be considered.

An analysis of the distribution of flash origin distances from core radar echoes indicates that the mean distance inside the 40-dBZ composite reflectivity echoes was slightly greater in the synoptic cases. But, 90% of the flashes originated either inside the composite reflectivity core or within about 1 km of the edge of the core echo in both regimes; and 95% originated within 3 km of the 40-dBZ reflectivity core in both regimes, as well. The continuity in the spatial relationship between the flash origins and the radar reflectivity cores effectively minimizes any impact that an increase in the mean flash origin composite reflectivity might have on lightning warning guidance.

**4.3.2. Flash Distances.** A significant difference exists in the distribution of maximum flash distance from the flash origin, and a modest difference in maximum flash distance from the 40-dBZ echos, for the two weather regimes. A comparison of the CDF's of maximum flash distance from the flash origin is shown in Figure 15. The mean maximum flash horizontal distance for the synoptic days was 8.2 km (4.4 NM), and 6.4 km (about 3.5 NM) for the airmass days. The 90<sup>th</sup> and 95<sup>th</sup> percentiles, however, show a more pronounced difference. 90% of flashes on airmass days have a horizontal extent of less than 13 km, compared to 18 km on synoptic days. 95% of flashes on the airmass days had a maximum flash horizontal distance from the flash origin of less than 17 km; under synoptic conditions, this 95<sup>th</sup> percentile extends out to 22 km. The same trend toward greater flash extent with synoptic forcing was found for maximum distance from the radar echo cores, although the differences observed were less than about 2 km between the two regimes.



**Figure 15. CDF Comparison of Maximum Flash Distance from Origin.** This graph shows that the 90% of all flashes traveled less than 13 km for the air mass days and 18 km for the synoptic days. Similarly, 95% traveled less than 17 km under air mass conditions and 22 km on synoptic days.

## **V. Conclusion**

### **5.1. Conclusions**

The goal of this research was to examine the possibility of establishing guidance for aircraft lightning avoidance and lightning warning criteria based upon the radar reflectivity signatures of lightning flash origins. Based upon the results of this investigation, it does appear feasible to come up with such guidance—both for in-flight thunderstorm avoidance and cloud-to-ground lightning safety criteria—that uses the radar reflectivity characteristics of lightning source points as basis for threat area identification. The use of the 40-dBZ threshold—which was selected primarily because it is the lower limit of the maximum reflectivity displayed by the C-17’s radar system—proved to be an adequate value for the analysis of flash origin spatial distribution.

It was shown that 95% of the lightning flashes studied originated within 3 km of a 40-dBZ composite reflectivity echo, with 80% of the flashes actually originating within the 40-dBZ composite reflectivity echoes. The 40-dBZ composite reflectivity line could be used as a trigger for when to issue, or cancel, weather warnings for lightning at Air Force installations. For example, issue a warning once the 40-dBZ line of an active thunderstorm—as determined by National Lightning Detection Network (NLDN) indications of CG lightning activity—comes within 7 NM of the warning area (assuming that the 5 NM radius is used). This could be especially important for Operational Weather Squadron (OWS) forecasters responsible for issuing warnings for all bases within their area.



When these results are combined with the findings of Captain Todd McNamara's study of CG lightning distances from flash origin points, the adequateness of the current five nautical mile warning radius may warrant further scrutiny by Air Force weather and safety policy makers. In addition, the information that can be obtained when lightning and radar data are combined emphasizes the requirement for better-integrated lightning observing systems. This is especially true after the advent of the OWS, where warning responsibility rests with someone outside the local area. The task of keeping track of multiple bases and knowing when to issue/cancel lightning warnings would be eased greatly by integration of NLDN data with radar displays, and preferably with 3D lightning mapping systems at each base to provide a total lightning picture.

Merging the results of this project with Captain Dave Vollmer's investigation into flash distances by altitude and atmospheric temperature, could suggest an in-flight lightning avoidance rule-of-thumb that is based upon the radar echoes displayed by onboard radars. The flash distance results derived in this study—which are, admittedly, less exhaustive than the forthcoming results from Captain Vollmer's research—suggest that 95% of lightning flashes extend less than 19 km (10.25 NM), and 99% traveled less than 30 km (16.1 NM), horizontally from the flash origin. The base reflectivity analysis of more than 8,500 flash origin points revealed that 95% of the flashes originated within 6 km (or 3.2 NM) of the nearest 40-dBZ base reflectivity radar echo. Using the 99<sup>th</sup> percentile of observed flash distance (30 km), for optimum safety concern, suggests a safe avoidance distance of about 36 km (just under 20 NM) from the nearest 40-dBZ radar return.

The data also suggest that a less restrictive threshold could be considered based upon the observation that 99% of all flashes traveled no further than 21 km 3D distance (about 11.3 NM) from the nearest 40-dBZ echo. The results from this study show great promise for coming up with practical guidance for lightning safety based upon radar echoes for both weather personnel and aircrew members. There is one main limiting factor that will be discussed in the next section, however, that would—at least at this time—most likely preclude widespread guidance being developed based upon these findings.

## **5.2. Recommendations for Future Work**

The fact that all the data used for this research came from the KSC area, may suggest that the potential guidance stemming from this research might be valid only for flight and ground operations near the KSC. Perhaps the results might be representative of thunderstorms in the southeast United States, but what about the rest of the CONUS? To address the limitations on the applicability of the findings in this study, 3D lightning data from different geographical regions should be studied in the same manner.

Until recently, the only other 3D lightning mapping system in the United States was the system owned by New Mexico Tech for research purposes. There is, however, a new system, similar to LDAR, being operated in the Dallas, Texas area on an experimental basis. The possibility of obtaining data from this system, and merging it with WSR-88D coverage of the Dallas area, could provide an opportunity to validate, or perhaps to identify a regional bias in, the findings of this study. The Dallas data may also present the opportunity to study different types of thunderstorms, such as supercells and mesoscale convective complexes.

## Appendix A. IDL Flash Grouping Program

The flash-grouping computer code, written for the Interactive Data Language (IDL) environment, that was developed using the NASA flash-grouping algorithm as a blueprint is presented in this appendix. This code is included to allow an examination of the logic used to group individual LDAR data points into lightning flashes. The code accepts the file name of the raw LDAR data file to be processed and uses the same file name to save the resulting flash-grouped LDAR file. The raw LDAR data is assumed to be in the standard ASCII text format used by NASA. The comment lines, marked by a semicolon, explain what each section of code is doing.

```
;*****
; Creates a Const structure to hold constants that can be passed from
; function to function by only passing one argument
;*****

FUNCTION Const
  C = {C, xcal:-1318L, $ ; xpos of calibration data
      ycal:-1609L, $ ; ypos of calibration data
      zcal:450L, $ ; zpos of calibration data
      dx:200L, $ ; look +/- 200m from xcal
      dy:200L, $ ; look +/- 200m from ycal
      dz:450L, $ ; look +/- 450m from zcal
      max_flash_time:3.0D, $ ; max 3 sec from start/stop of flash
      max_flash_delay:0.5D, $ ; max time lag between points in flash
      max_branch_delay:0.03D, $ ; max delay between points in a branch
      Pi:3.14159265359, $
      deg_to_rad:3.14159265359/180.0, $ ; degree to radian conversion
      angle_error:1.0D, $ ; directly from NASA code
      max_dis_f:5000.0D, $ ; point must be within 5km to be in flash
      block_size:500L } ; examine 500 LDAR data lines at a time
  RETURN, C
END
```

```

;*****
; data_line Structure definition. LDAR data files will be read directly
; into this structure. (Note: ms, x, y, z are LONG integers)
;*****

```

```

FUNCTION data_line
    DL = {DL, day:0,      $
          hr:0,          $
          min:0,         $
          sec:0,         $
          ms:0L,         $
          x:0L,          $
          y:0L,          $
          z:0L }
    RETURN, DL
END

```

```

;*****
; point_struct definition. This structure will hold the seconds (time),
; flash number (fnum), branch number (bnum), point number (index), line
; number of the parent point (parent), and line number (line_num) of
; each non_calibration data point found.
;*****

```

```

FUNCTION point_struct
    p = {p, time:0.0D, $
          fnum:0L,     $
          bnum:0L,     $
          index:0L,    $
          parent:0L,   $
          line_num:0L}
    Return, p
END

```

```

;*****
; flash_struct definition. Temporary structure that will hold the start
; time (start_time) in seconds, end time (end_time) in seconds, number
; of points (num_points), number of branches (num_branches), and the
; line number of the first point (first_point) in a flash.
;*****

```

```

FUNCTION flash_struct
    FL = {FL, start_time:0.0D, $
          end_time:0.0D,      $
          num_points:0L,      $
          num_branches:0L,    $
          first_point:0L }
    RETURN, FL
END

```

```

;*****
; branch_struct definition. This temporary structure will hold the
; start time (start_time) in seconds, end time (end_time) in seconds,
; number of points (num_points), line number of the first (first) point,
; line number of the last identified point (last), line number of the
; closest point (parent) in the flash to the first point, flash number
; (fnum), and branch number (bnum) for an active branch.
;*****

FUNCTION branch_struct
    BR = {BR, start_time:0.0D, $
          end_time:0.0D, $
          num_points:0L, $
          first:0L, $
          last:0L, $
          parent:0L, $
          fnum:0L, $
          bnum:0L }
    RETURN, BR
END

;*****
; Calculates the 3-Dimensional distance between two points. This
; function accepts two point_struct type arguments p1 & p2 and uses
; pythagoream's rule to determine the 3D distance.
;*****

FUNCTION dist_between_2_points, p1, p2
    RETURN, sqrt(((p1.x*1.0D) - (p2.x*1.0D))^2 + $
                ((p1.y*1.0D) - (p2.y*1.0D))^2 + $
                ((p1.z*1.0D) - (p2.z*1.0D))^2)
END

;*****
; Calculates the 2-Dimensional horizontal distance between two points.
; This function accepts two point_struct type arguments p1 & p2 and uses
; pythagoream's rule to determine the 2D horizontal distance.
;*****

FUNCTION h_dist_between_2_points, p1, p2
    RETURN, sqrt(((p1.x*1.0D) - (p2.x*1.0D))^2 + $
                ((p1.y*1.0D) - (p2.y*1.0D))^2)
END

;*****
; range_error was directly taken from the NASA flash grouping algorithm.
;
; This function expects a floating point number that represents the
; horizontal distance (in meters) from the LDAR site to the LDAR event.
; The range error is determined to be 12% of the range (i.e. if an event
; is 50km from the LDAR site, the range error is 6km).
;*****

FUNCTION range_error, r
    return, (r * 12.0D/100.0D)
END

```

```

;*****
; max_dis_b was directly taken from the NASA flash grouping algorithm.
;
; The function expects a floating point number that represents the
; horizontal distance (in meters) from the LDAR site to the LDAR event.
;
; If a data point is within 40km of the LDAR site, a max horizontal
; distance of 1km is used to determine if a point is within branch
; bounds. Outside of 40km, this distance increases from 1km by a factor
; of r/40km.
;*****

```

```

FUNCTION max_dis_b, r
    If (r LT 40000.0) THEN return, 1000.0d ELSE return, r/40.0d
END

```

```

;*****
; is_point_in_flash_bounds is a modified version of the function in the
; NASA flash grouping algorithm by the same name.
;
; This function is the key to determining whether or not a point is part
; of a flash based upon spatial constraints. The variables passed to
; the function are the point to be checked (p1 : sub_d[checki]] from the
; main program), the group of data being examined (data : sub_d from the
; main program), the group of points being examined (p : sub_p from the
; main program), the flash number of the origin of the flash being
; examined (fnum : sub_p[init].fnum from the main program), the origin
; data point (origin...has location [0,0,0]), and the constant structure
; C.
;
; To determine if a point is within flash bounds, the radius defined in
; the constant structure (C) is used (Default value of 5000km could be
; modified prior to compiling and running the program. This radius is
; stored in the C.max_dist_f constant.
;
; An ellipse with a minor axis perpendicular to the radial between the
; LDAR site and the point being considered and a major axis along
; that radial is used to determine whether or not a point is within the
; spatial bounds to be grouped in with a flash. The minor axis is a
; function of C.max_dist_f plus the azimuthal error of LDAR. The major
; axis is also a function of C.max_dist_f but is mainly influenced by
; the range error of the LDAR system.
;
; The function returns a 1 if the point is within flash bounds and a 0
; if the point is not in flash bounds.
;*****

```

```

FUNCTION is_point_in_flash_bounds, p1, data, p, fnum, origin, C

```

```

; locate all points in the flash
    find = where(p.fnum EQ fnum, cnt)

; p2 is an array of all data points in the current flash
    p2=data[find]

; thetai indicates the angle from the LDAR point to the point p1
    thetai = atan (p1.y , p1.x )

; loop through all points (if necessary)
    for j = 0L , cnt-1L DO Begin

; make sure there is no divide by zero problem with finding theta2

```

```

; by adding 1m to p1.x if x's are equal
    if (p2[j].x EQ p1.x) then p1.x = p1.x + 1.0

; theta2 is the angle between the current flash point and point p1
    theta2 = atan ((p2[j].y - p1.y) , (p2[j].x - p1.x))

; alpha is the difference in the two angles, and represents the angle
; between a line connecting the LDAR site to point p1 and point p2
    alpha = theta1 - theta2

; determine the distance to point p1 from the LDAR site (2D)
    range = h_dist_between_2_points ( origin , p1 )

; calculate distance between p1 and the current point in the flash (2D)
    dis = h_dist_between_2_points ( p1 , p2[j] )

; a is the minor axis of the ellipse around p1 and represents the
; azimuthal error of the LDAR system
    a = C.max_dis_f + C.angle_error * C.deg_to_rad * range

; b is the major axis of the ellipse around p1 and represents the range
; error of the LDAR system
    b = C.max_dis_f + range_error( range )

; y is the component of the distance between p1 and p2 that is parallel
; to the radial from the LDAR site to point p1
    y = dis * cos ( alpha )

; if y is greater than the major axis of the ellipse there is no way
; that this point is part of the flash...also avoids an imaginary
; number when calculating x...
    if (abs(y) LE abs(b)) then Begin

; solve the equation of the ellipse for x (all other variables are known
    x = a * sqrt ( 1. - y*y/(b*b) )

; determine the vector distance (in ellipse coordinates) to the point
; x, y on the ellipse...
    dis_allowed = sqrt ( x*x + y*y )

; If the distance to p2 is less than dis_allowed, p2 must fall inside
; the ellipse and is included in the flash...return 1 to the main
; program to indicate success. This prevents the loop from continuing
; once the point has been determined to belong with the flash...
    if ( dis LE dis_allowed ) Then return, 1

endif; end of If (abs(y) LE abs(b))...

endifor

; If we've looked at all points in the flash and none are close enough
; tell main program this point is not part of flash...
    return, 0
END

```

```

;*****
; is_point_in_branch_bounds is a modified version of the function in the
; NASA flash grouping algorithm by the same name.
;
; This function determines whether or not a point is part of a branch
; based upon spatial constraints. The variables passed to the function
; are the point to be checked (p1 : sub_d[check1]] from the main
; program), the branch number to check (bn : bnum from the main
; program), the group of data being examined (data : sub_d from the main
; program), the temporary branch structure array (b), and the origin
; data point (origin...has location [0,0,0])
;
; The function returns a 1 if the point is within branch bounds and a 0
; if the point is not in branch bounds.
;*****

```

**FUNCTION is\_point\_in\_branch\_bounds, p1, bn, data, b, origin**

```

; determine the 2D range from the LDAR site to point p1
  range = h_dist_between_2_points ( origin , p1 )

; Check the distance between p1 and the last point in the current branch
; and compare the result with the result of the call to max_dis_b for
; the range that p1 is from the LDAR site...
  if (h_dist_between_2_points(p1,data[b[bn].last]) LE $
      max_dis_b(range)) Then return, 1 else return, 0
END

```

```

;*****
; find_closest_point_in_flash is called if a point is found to be within
; flash bounds, but is not part of any branch, and is therefore the
; first point in a new branch. This function determines which point in
; the flash is closest and that point will be the "parent" of this new
; branch.
;
; This function is passed both the data structure and the point
; structure of the point to be checked (d1 : sub_d[check[i]]
; from the main program and pt1 : sub_p[check[i]] from the main
; program), as well as the data and point sets being examined (p : sub_p
; from the main program and data : sub_d from the main program).
;
; The 3-Dimensional distance between all the points in the flash and pt1
; are calculated and a pointer to the closest point is returned.
;*****

```

**FUNCTION find\_closest\_point\_in\_flash, d1, pt1, p, data**

```

; Find all points with the same fnum...but don't include point pt1...
  j = where((p.fnum EQ pt1.fnum) AND (p.time NE pt1.time))

; dist will be a vector of distances calculated between all points & pt1
  dist = dist_between_2_points(data[j],d1)

; find the shortest distance
  shortest = min(dist)

; get a pointer to the element that is closest...
  index = where(dist EQ shortest, count)

; if there are more than one point with same distance...return the first
  if (count EQ 1) then return, j[index] else return, j[index[0]]
END

```



```

;*****
; Summary of Revisions:
; Version          Date          Changes
; =====
; 1.0              13 Jul 01      Started working on it...
; 1.1              19 Jul 01      Modified with dialog_pickfile()
; 1.2              20 Jul 01      Started using Structures...
; 1.3              28 Aug 01      Bite-Sized Chunks added
; 1.4              04 Sep 01      Finished coding...it works!!!!!!!
; 1.5              24 Oct 01      Completed Documenting Code
;*****
; Program flash_group.pro
;
; Date: 24 Oct 2001
;
; Version: 1.5
;
; Written By: 1Lt Lee A. Nelson
;
; Purpose: flash_group reads in an ASCII text file from a user-specified
; location (either at the command prompt on the program call, or in a
; script file, or by use of a dialog pickfile window if no filename is
; declared when the program is called).
;
; The logic for this code comes from the LDAR flash grouping C program
; used by NASA. Very slight modifications were necessary in the logic
; of the program. The entire file interface is different from the NASA
; algorithm.
;
; The output file are saved in ASCII text format using the identical
; file name as the LDAR input file. As such, the location that a file
; is saved to is very crucial. As with our LDAR input files, the naming
; convention is:
;
; ldarYYYYMMDD.txt
;
; YYYY - Year
; MM - 2 Digit Month
; DD - 2 Digit Day
;
; The data in the output file includes all data in the original LDAR
; text files: Julian Date, Hour, Minute, Second, Microsecond, X, Y, and
; Z locations, plus the following columns of data:
;
; Flash Number: (note a flash number of -1 indicates that this point
;                was either a lone point or there was only one point
;                with flash bounds, and no two-point flashes are
;                considered to be valid events)
;
; Branch Number: (note: the origin of a flash is branch number 0)
;
; Point Number (or index): (indicates position within a branch...flash
;                           origin is Point 0)
;
; Parent: (the first point in a branch will have a parent, this is the
;          point in the flash that is closest to the first point in a
;          branch...most points will not have a parent...in general only
;          points with a point number of 1 will have a valid number in
;          the parent column)
;
; Line Number: (a unique index number for the data line, useful as a
;               pointer and a sub-reference when only parts of a data

```

```

;               set is being examined)
;
; The IDL Format statement to read these output files is:
;
; format = '(i3,lx,i2,lx,i2,lx,i2,lx,i6,lx,i9,lx,i9,lx,i9,lx,i7' + $
;           ',lx,i7,lx,i7,lx,i7,lx,i7)'
;*****

pro flash_group, fname = fname

    close,/all          ; Ensure all files are closed

    C=Const()           ; call Const() function to define constants...

    inpath = '/home/fujita12/ldar/data/' ; modify if necessary
    outpath = '/home/fujita7/nelson/flash/' ; modify if necessary

; Note: the outfile has the identical name as the original LDAR file...
    infile = inpath+fname
    outfile = outpath+fname

    print, infile      ; show name of input file on screen

    n=0L               ; initialize the line count holder

    clock = systime(1)   ; initialize the clock to determine run time

    openr, input, infile, /get_lun

    while not (eof(input)) do begin ; loop to count lines of data
        readf, input, s
        n = n + 1L
    endwhile

    point_lun, input, 0   ; reset pointer to first line of file

    Line = data_line()    ; Call to data_line() creates a blank structure

    data = replicate(Line,n) ; make an array of structures to hold data

    readf, input, data ; fill the array from the LDAR file

    close, input ; close the LDAR file
    free_lun, input ; free the pointer

; Filter out Calibration Data by creating an array of pointers to the
; data that is outside of the calibration "box"
    filter = where(((data.x LE (c.xcal-c.dx)) OR $
                    (data.x GE (c.xcal+c.dx))) OR $
                    ((data.y LE (c.ycal-c.dy)) OR $
                     (data.y GE (c.ycal+c.dy))) OR $
                    ((data.z LE (c.zcal-c.dz)) OR $
                     (data.z GE (c.zcal+c.dz)))), count)

; if there is calibration data in the file...ignore it...if there is
; only calibration data in the file...reset the data array to one blank
; structure
    if (count NE 0) then data = data[filter] else data = data_line()

; there may be some "roll-over" in the data, assume the first line is
; on the first day of data and assign this to the variable date...
    date = data[0].day

```

```

; This filters out any data with date/time data that is not correct...
; this came about because some corrupted data was found that had bad
; date data and garbage positional data...
    keep = where(((data.day EQ date) OR (data.day EQ date+1) AND $
                  (data.hr LE 23) AND (data.min LE 59) AND $
                  (data.sec LE 59) ), count)

; keep any "valid" data...if none...reset data array to one blank data
; structure
    if (count NE 0) then data = data[keep] else data = data_line()

; reset the counter to the data elements left after filtering
    n = n_elements(data)

; call the point_struct() function to define a point structure then
; make n copies of the structure to hold the information for each
; point in the data array
    p = point_struct()
    p = replicate(p,n)

; initialize the line_num elements of p
    p.line_num = lindgen(n)

; convert the time elements of the data array to seconds and store in
; the time element of p
    p.time = ((data.day - data[0].day)*86400.0D) + (data.hr*3600.0D) + $
              (data.min*60.0D) + (data.sec) + (data.ms/10.0D^6)

; define the origin...(note x,y,z = 0)
    origin = data_line()

; initialize the number of flashes and number of branches...
    num_flashes = 0L
    num_branches = 0L

; low and hi will keep track of which elements of the data and p arrays
; are being checked...
    low = 0L
    hi = C.block_size - 1L

; if there are more elements in the data and p arrays than C.block_size
; make a sub_d and sub_p array that holds C.block_size elements. If it
; is a small data set with C.block_size elements or less, then make the
; sub_d and sub_p arrays only hold n elements. The critical_t variable
; indicates the time that will trigger the need to read further elements
; into the sub_d and sub_p arrays. This critical time is determined by
; subtracting C.max_flash_time seconds from the last element in the sub
; array. If we try to examine any point as the possible origin of a new
; flash that is within C.max_flash_time of the end of the block, we need
; to get more points to ensure that all points are being considered that
; could be part of the flash...
    if (n GT C.block_size) then begin
        sub_d = data[low:hi] ; subset of data to be checked
        sub_p = p[low:hi] ; subset of p to be checked

; critical_t will trigger the process of getting another block of data
        critical_t = sub_p[hi].time - C.max_flash_time

; prepare for the next block of data to be checked...reset low and hi
        low = low + C.block_size
        hi = hi + C.block_size

    endif Else Begin ; if this is a small data set...only one block

```

```

        sub_d = data
        sub_p = p
        hi = n ; this will ensure no more blocks of data are checked
        critical_t = sub_p[hi-1L].time - C.max_flash_time
    endelse

; stop is a flase flag that allows entry into the while loop, exiting
; the loop is handled by a break statement once conditions are met...
    stop = 0

; this loop repeats until there are no more points to examine...
    while (stop NE 1) DO Begin

; define a blank branch structure (note: this discards any data from
; prior flashes...
        b = branch_struct()

; init is a pointer to the first element with a flash number of zero
        init = min(where(sub_p.fnum EQ 0, count))

; make sure there is at least one point with a flash number of zero
        if (count EQ 0) then Begin ; if there is not...

; if this the last last block of data (i.e. hi = n) then stop the loop
            if (hi EQ n) then break $; exits while loop...

; if there are more points...get another block of data...
            else begin

; if there are more than C.block_size points left...then
                if (hi + C.block_size LT n) then begin

; get the next block of data from low to hi
                    sub_d = data[low:hi]
                    sub_p = p[low:hi]

; define the new critical_t
                    critical_t = p[hi-1L].time - C.max_flash_time

; reset the low and hi pointers for the next block of data
                    low = low + C.block_size
                    hi = hi + C.block_size

; or if there are less than C.block_size points left...
                endif Else Begin

; get the remainder of points to be checked
                    sub_d = data[low:n-1L]
                    sub_p = p[low:n-1L]

; set hi = n to trigger check that no more data left...
                    hi = n

; set new critical_t
                    critical_t = p[hi-1L].time - C.max_flash_time

                endelse

; now go back to the first statement in the WHILE loop and look again
                Continue

            endelse
        endif ; ends the IF (COUNT EQ 0) statement...
    endwhile
enddo

```

```

; If we're near the end of the block (time-wise) and this isn't the last
; block of data to check, filter out the data that has already got a
; flash number, and then add another block of data to what's left in
; sub_d and sub_p...
    if ((sub_p[init].time GT critical_t) AND (hi NE n)) THEN Begin

; we'll keep all the points that haven't been assigned a flash number
    keep = where(sub_p.fnum EQ 0, cnt)
    sub_p = sub_p[keep]
    sub_d = sub_d[keep]

; if there are at least C.block_size elements left in data and p...
    if (hi + C.block_size LT n) then begin

; append another block from low to hi on to sub_d and sub_p
        sub_d = [sub_d,data[low:hi]]
        sub_p = [sub_p,p[low:hi]]

; calculate a new critical_t
        critical_t = p[hi-1L].time - C.max_flash_time

; reset low and hi for next block of data
        low = low + C.block_size
        hi = hi + C.block_size

; if there are less than C.block_size points left...
    endif Else Begin

; get the rest of the points and append to sub_d and sub_p
        sub_d = [sub_d,data[low:n-1L]]
        sub_p = [sub_p,p[low:n-1L]]

; set hi = n to trigger flag that this is last block of data
        hi = n

; determine new critical_t
        critical_t = p[hi-1L].time - C.max_flash_time
    endelse

; now, go back to first statement in WHILE loop and start again...
    continue
endif

; note: only get here if the all the points within C.max_flash_time
; seconds are included in this block of data, or if this is the last
; part of the data file and no more data can be added to sub_d and
; sub_p

; check is an array of pointers to the elements of sub_p and sub_d that
; are within C.max_flash_time seconds of the time of the point that init
; points to and have no flash number yet assigned...
    check = where ( (sub_p.time GT sub_p[init].time) AND $
                    (sub_p.time LE (sub_p[init].time + C.max_flash_time)) $
                    AND (sub_p.fnum EQ 0), count)

; if we don't find any points that meet the above criteria...set fnum to
; -1 to indicate not part of a valid flash...
    if (count EQ 0) then begin
        sub_p[init].fnum = -1L

; use the line_num of the sub_p element to reference the actual data
; in the p array and set fnum to -1 as well

```

```

        p[sub_p[init].line_num].fnum = -1L

; if there are points to check...check them
        endif ELSE Begin

; initialize a temporary flash structure...
        f_temp = flash_struct()
        f_temp.first_point = sub_p[init].line_num
        f_temp.start_time = sub_p[init].time
        f_temp.end_time = f_temp.start_time
        f_temp.num_points = f_temp.num_points+1

; initialize the flash number of the init point...
        sub_p[init].fnum = num_flashes+1L
        p[sub_p[init].line_num].fnum = num_flashes+1L

; initialize a temporary branch structure
        b_temp = branch_struct()
        b_temp.fnum = num_flashes+1L
        b_temp.parent = sub_p[init].line_num ; init is parent...

; recall that count is the number of points in check...that is, the
; number of points with no flash number and within C.max_flash_time
; seconds of init...
        for i = 0L, count-1 DO Begin

; check to see if the point is within the proper temporal (within
; C.max_flash_delay seconds of the last point in the flash) and
; spatial window to be considered part of the flash...
                if (((sub_p[check[i]].time-f_temp.end_time) LE C.max_flash_delay) $
                    AND (is_point_in_flash_bounds(sub_d[check[i]], $
                        sub_d,sub_p,sub_p[init].fnum,origin,C) EQ 1)) $
                    THEN Begin ; if it is within time and space bounds...

; set flash number in sub_p and p...
                        sub_p[check[i]].fnum = sub_p[init].fnum
                        p[sub_p[check[i]].line_num].fnum = sub_p[init].fnum

; set flash end_time to this point's time
                        f_temp.end_time = sub_p[check[i]].time

; increment the number of points in the flash...
                        f_temp.num_points = f_temp.num_points+1L

; check to see if this is the first branch in the flash...if it is...
                        if (f_temp.num_branches EQ 0) then Begin

; initialize the branch information for the first point...
                                sub_p[check[i]].bnum = 1L
                                sub_p[check[i]].index = 1L
                                p[sub_p[check[i]].line_num].bnum = 1L
                                p[sub_p[check[i]].line_num].index = 1L

; initialize the b_temp information with the info from the current point
                                b_temp.start_time= sub_p[check[i]].time
                                b_temp.end_time = b_temp.start_time
                                b_temp.first = check[i]
                                b_temp.last = check[i]
                                b_temp.bnum = 1L
                                b_temp.num_points = 1L
                                f_temp.num_branches = 1L
                                b = [b,b_temp]; add branch to structure

```

```

; note: the parent is the line_num of init...
      sub_p[check[i]].parent = b_temp.parent
      p[sub_p[check[i]].line_num].parent= b_temp.parent

; if there is already at least one branch in the current flash...
      endif else Begin

; found is a flag to stop looping once we find a branch for this point
      found = 0

; look through all branches to determine if point is part of a branch
      for j = 1L,f_temp.num_branches Do Begin

; if we haven't found a branch...then
      if (found EQ 0) Then Begin

; Check if point is within temporal (C.max_branch_delay seconds) and
; spatial bounds of the last point in the current branch
      if ((sub_p[check[i]].time - b[j].end_time LE $
          C.max_branch_delay) AND (is_point_in_branch_bounds $
          (sub_d[check[i]], j, sub_d, b, origin) EQ 1)) $
          Then Begin ; if part of this branch

; set end_time of branch...
          b[j].end_time = sub_p[check[i]].time

; increment number of points in this branch...
          b[j].num_points = b[j].num_points + 1L

; set branch number of point in sub_p and p...
          sub_p[check[i]].bnum = j
          p[sub_p[check[i]].line_num].bnum = j

; set index number for this point in p and sub_p...
          p[sub_p[check[i]].line_num].index = b[j].num_points
          sub_p[check[i]].index = b[j].num_points

; set pointer to the last element of the branch to current point...
          b[j].last = check[i]

; set flag to stop looping for this point...
          found = 1
      endif
    endif
  endfor

; if we didn't find a branch for the point...must be a new branch...
      if (found EQ 0) Then Begin

; find the closes point in the flash to this point...
      nearest = find_closest_point_in_flash (sub_d[check[i]], $
          sub_p[check[i]], sub_p,sub_d)

; create a new brach element...
      b_temp = branch_struct()

; parent of new branch is nearest point in the flash...
      b_temp.parent = sub_p[nearest].line_num

; assign parent to sub_p and p point as well...
      p[sub_p[check[i]].line_num].parent = b_temp.parent
      sub_p[check[i]].parent = b_temp.parent

```

```

; assign flash number
    b_temp.fnum = sub_p[check[i]].fnum

; initialize first and last of new branch element...
    b_temp.first = [check[i]]
    b_temp.last = check[i]

; increment number of branches in the flash...
    f_temp.num_branches = f_temp.num_branches + 1L

; assign a branch number to the new branch...
    b_temp.bnum = f_temp.num_branches

; initialize the start and end time of the new branch...
    b_temp.start_time = sub_p[check[i]].time
    b_temp.end_time = sub_p[check[i]].time

; set the number of points in the new branch to 1
    b_temp.num_points = 1L

; update p and sub_p with branch number & index
    p[sub_p[check[i]].line_num].bnum = b_temp.bnum
    sub_p[check[i]].bnum = b_temp.bnum
    sub_p[check[i]].index = 1L
    p[sub_p[check[i]].line_num].index = 1L

; append b_temp to b...
    b = [b,b_temp]
endif ; end of IF (found EQ 0)...
endelse

endif

endfor ; end of for loop to check all points...

; note: we get here when we've checked all points

; A flash will only be considered valid if there are more than 2 data
; points in the flash...
    If (f_temp.num_points GT 2) THEN Begin ; if a valid flash...

; increment number of flashes...
    num_flashes = num_flashes+1L

; complete indicates the percentage of points examined thus far...it
; is echoed to the screen as a visual check for how much progress is
; being made...
    complete = ((sub_p[init].line_num*1.0) / $
                (n_elements(data)*1.0))*100.0

; show the progress on the screen (flash number, % done, etc...
    print, complete, '% flash number: ', num_flashes, $
        ' index: ', sub_p[init].line_num, ' time :', $
        sub_d[init].day, sub_d[init].hr, sub_d[init].min, $
        sub_d[init].sec, sub_d[init].ms, $
        format = "(f6.2,a16,i8,a8,i8,a7,4i3,i7)"

; if this was not a valid flash (i.e. not more than 2 points in flash)
    endif else Begin

; set init point flash number to -1 to indicate not a valid flash...
    sub_p[init].fnum = -1L

```



```

        p[sub_p[init].line_num].fnum = -1L

; find the points in sub_p that were part of this possible flash...
        reset = where(sub_p.fnum EQ num_flashes +1L, count)

        if (count NE 0) then Begin

; find the points in p that were part of this possible flash, too...
        reset2 = where(p.fnum EQ num_flashes + 1L)

; reset the flash number, parent, and index of each point...
        sub_p[reset].fnum = 0L
        sub_p[reset].parent = 0L
        sub_b[reset].index = 0L
        p[reset2].fnum = 0L
        p[reset2].parent = 0L
        p[reset2].index = 0L
        endif
    endelse
endelse
END ; end of while loop

; open the output file for writing...
    openw, output, outfile, /get_lun

; write the output for each line of data in the data and p arrays...
    for i = 0L, n_elements(p) - 1 DO begin
        printf, output, data[i].day, data[i].hr, data[i].min, $
            data[i].sec, data[i].ms, data[i].x, data[i].y, data[i].z, $
            p[i].fnum, p[i].bnum, p[i].index, p[i].parent, $
            p[i].line_num, format = "(4i3,i7,3i10,5i8)"
    endfor

    close, /all ; close all files
    free_lun, output ; free the pointer to the output file...

; echo to the screen how many points were not part of a flash...
    print, n_elements(where(p.fnum LT 0)), ' item(s) out of ', $
        n_elements(p), ' were not part of a flash'

; echo to screen how long it took to complete the program...
    print, 'It took ', systime(1)-clock, ' seconds to run this...' , $
        format = "(a8,f12.1,a23)"

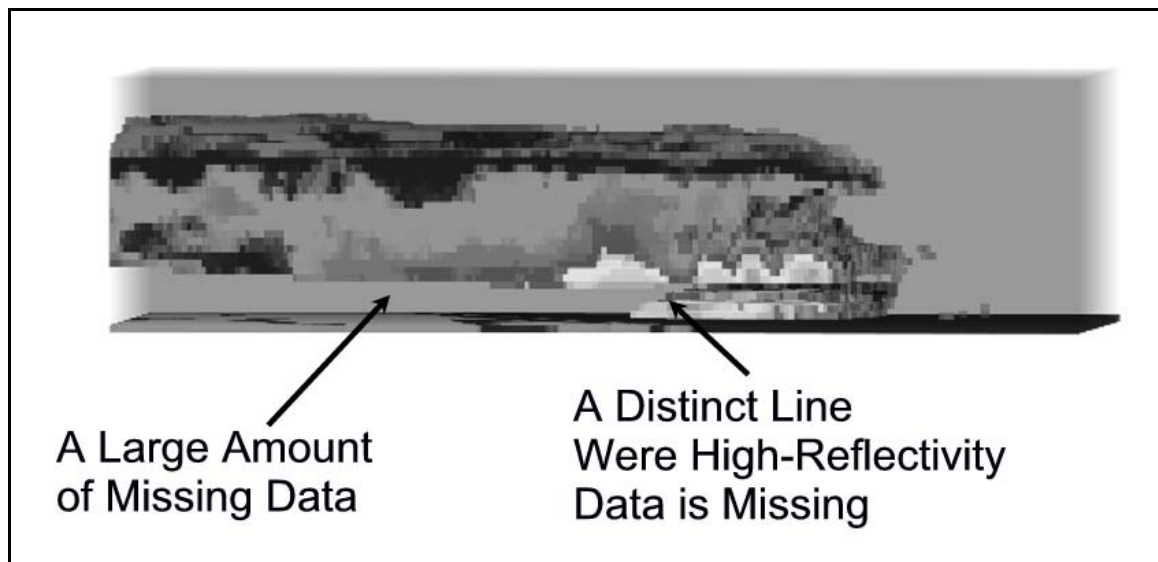
; echo to screen that the program execution is complete...
    print, 'done...'

end ; end of Program

```

## Appendix B. Examples of Radar Processing Errors

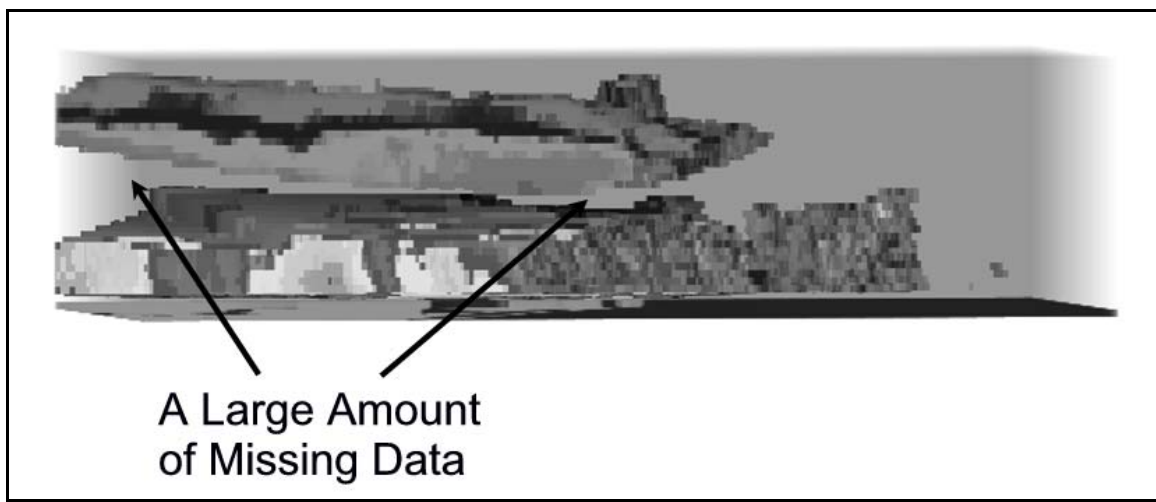
Two figures are include in this appendix to graphically show two of the types of data problems found when using the SPRINT and CEDRIC software to interpolate archive Level II radar reflectivity data to a 3D Cartesian grid. Figure 16 shows a radar volume that was deemed unusable due to the large amount of missing data in the lower levels—were we'd expect to find some of the higher reflectivity returns. There is a distinct line that shows that only part of one of the elevation scans was processed, with several missing altogether.



**Figure 16. Example of an Unusable Radar Volume.** This image shows a radar volume that was considered unusable because crucial reflectivity information is missing. The distinct line of where the reflectivity is missing, combined with the fact that much of the lower levels of the radar echoes are missing, makes this volume unfit for even composite reflectivity calculations.

Figure 17 is an example of a radar volume that was declared to be partially usable. This indicates that some of the data is missing, but a subjective analysis indicated that enough of the higher reflectivity values are present that would facilitate a composite

reflectivity grid being created from the valid data in the volume. In the volume shown, there is a large slice of the mid levels of the storm missing, but it is clear that most of the higher reflectivity values are included in the available data. Radar volumes such as this were used for composite reflectivity calculations—and the distance calculations based upon composite reflectivity grids. These partially usable volumes were not used, however, for any base reflectivity computations.



**Figure 17. Example of a Partially Usable Radar Volume.** This image shows a radar volume that was considered partially usable. A rather large slice of the volume is missing, however, it lies above the region of highest reflectivity, making it very likely that a composite reflectivity grid created by a complete volume and one created from this 3D grid would be essentially equivalent.

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## Vita

1Lt Lee Nelson was born (and will die) a Minnesota Vikings fan. Born and raised in the Land of 10,000 Lakes, he is rumored to actually bleed purple. He graduated from Barrett Public High School in Barrett, Minnesota. After attending the University of Minnesota at Morris for two quarters, he enlisted in the U. S. Air Force and was trained as a Target Intelligence Specialist. He continued his education at night over the next several years and eventually entered the Palace Chase program and moved back to Minnesota. There he attended North Dakota State University for a year and served in the North Dakota Air National Guard before returning to active duty (again as a Target Intelligence Specialist). In 1995, he applied for, and was accepted into, the Airman Education and Commissioning Program and moved to Greeley, Colorado to attend the University of Northern Colorado. In December 1997 he graduated *Summa Cum Laude* with a Bachelor of Arts degree in Earth Sciences-Emphasis in Meteorology, from the University of Northern Colorado.

1Lt Nelson was commissioned a 2<sup>nd</sup> Lieutenant in the Air Force on 24 April 1998 as a weather officer. His first assignment was to the 18<sup>th</sup> Weather Squadron at Fort Bragg, North Carolina where he was the XVIII Airborne Corps Assistant Staff Weather Officer.

His next assignment was to Wright-Patterson AFB, Ohio to attend the Air Force Institute of Technology to enter the graduate meteorology program. After graduation he is being assigned to the 607<sup>th</sup> Weather Squadron at Seoul, South Korea.

In addition to being a die-hard Vikings fan, he enjoys playing guitar and is an avid golfer. One of his favorite hobbies is building custom golf clubs.

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